

A Regional Assessment of the Economic and
Environmental Benefits of an Irrigation
Scheduling Service

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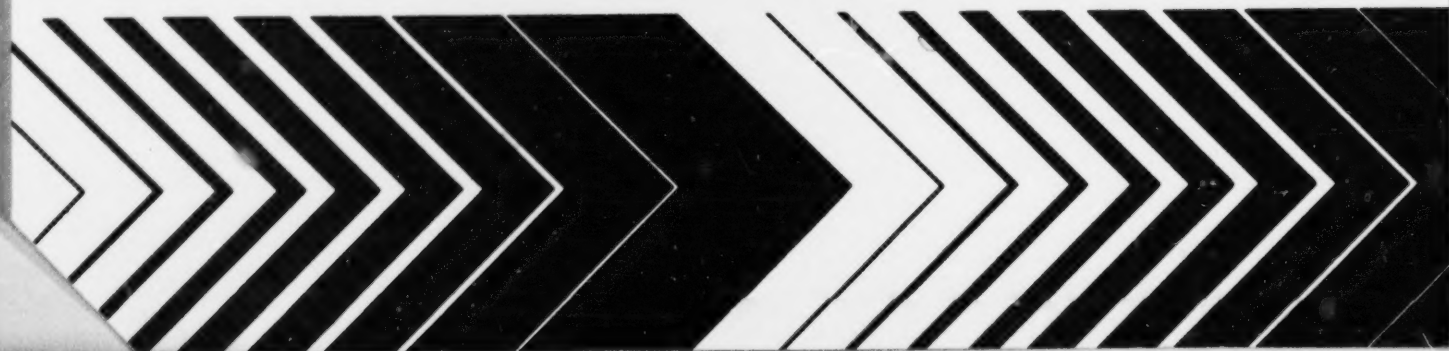
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A Regional Assessment of the Economic and Environmental Benefits of an Irrigation Scheduling Service

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BENEFITS OF AN IRRIGATION SCHEDULING SERVICE

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FOREWORD

Environmental protection efforts dealing with agricultural and nonpoint sources have received increased emphasis with the passage of the Clean Water Act of 1977 and the subsequent implementation of the Rural Clean Water Program. As part of this Laboratory's research on the occurrence, movement, transformation, fate, impact, and control of environmental contaminants, data and analytical methodologies are developed to assess the causes and possible solutions of adverse environmental effects of irrigated agriculture.

This report addresses the need for methodology to assess the regional economic aspects of implementing irrigation scheduling as a resource conservation and crop production tool. Water-use efficiency and economic efficiency must be weighed in environmental management decisions. This report should benefit environmental managers as they attempt to identify and implement pollution control strategies relevant to western irrigated agriculture.

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ABSTRACT

Irrigation scheduling is a technique for systematically determining the proper date and quantity of each irrigation in individual fields. This technique is presently being used by government agencies and private companies in the western United States to assist farmers in planning irrigations. This report describes a case study in which the regional environmental and economic benefits of irrigation scheduling were assessed. The analysis indicated that substantial environmental benefits could be realized through use of the technique. However, it was also found that imperfections which normally occur in actual irrigation scheduling operations could drastically reduce these benefits. The economics of irrigation scheduling appeared favorable in the particular circumstances of the case study.

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While all of the people mentioned above contributed in one way or another to this research, nevertheless the interpretation, analysis and write-up of this research were done by the authors, and any errors or oversights must be regarded as our responsibility.

SECTION 1

INTRODUCTION

In recent years a new approach to irrigation has emerged in which a computer is used, in combination with trained personnel working in the field, to determine the appropriate timing and amount of each irrigation for individual fields. The computer is used to model soil moisture conditions and forecast the required date and amount of upcoming irrigations. The field personnel interpret the computer outputs, periodically check soil moisture in the fields and advise the farmer on his irrigation schedule. This scheduling procedure is based upon principles of soil science, agronomy, meteorology and engineering and is often referred to as scientific irrigation scheduling. It was developed originally by Dr. Marvin Jensen of the U.S. Science and Education Administration (SEA) between 1968 and 1971, was modified and developed by the U.S. Bureau of Reclamation (USBR), the U.S. Soil Conservation Service (SCS) and others (Gear, et al., 1976; Buchheim and Ploss, 1977) and is now being applied as a commercial service to farmers throughout the Western United States. A comprehensive review of the theory, application and early results of irrigation scheduling has been written by Jensen (1975).

It is generally held that the potential benefits of an irrigation scheduling service (ISS) may include:

- a. reduced water use, with attendant reductions in drainage problems and reduced salinity of downstream flows,
- b. increased crop yields,
- c. reduced production costs for water, fertilizer, and pesticides, and
- d. improved farm operating efficiencies due to the ability to plan irrigations well ahead of time.

In practice, however, these benefits are often disputed. It has been found, for example, that water use increased in some fields when an ISS was used.* On the basis of some preliminary results, crop yields appear to have increased significantly in some areas, but only slightly or not at all

*This has been attributed to farmers following recommended schedules having shorter intervals between irrigations but not following recommendations for reduced water use (Jerry Buchheim, pers. comm.)

in other areas (USBR, 1974; Schaack, 1975). Many farmers have discontinued the use of scheduling services because they did not feel that they derived a net benefit from them (Jensen, 1975). In short, the advantages and disadvantages of an irrigation scheduling service have not been clearly established. There is therefore a need for comprehensive, systematic analyses of the benefits and costs of irrigation scheduling services. In order to objectively evaluate an irrigation scheduling service there is a need to:

- a. determine who does and who does not benefit from the service, and to what extent,
- b. give all interested individuals a clearer understanding of the benefits and costs of an ISS in order to assist them in making a decision to utilize the program, and
- c. assess the effectiveness of alternative ISS program configurations under different circumstances.

In light of these questions both the Environmental Protection Agency (EPA) and Bureau of Reclamation (USBR) have pointed out the need for comprehensive data collection programs in areas where scheduling services are being utilized (Jensen, 1975; USBR, 1972). Such programs are now underway at some USBR scheduling operations. Data are being collected from groups of farms which are using a scheduling service and from matching groups of farms which are not using such a service. The difference in water use and crop yields between the two groups should represent the benefits of a scheduling service. These comparative field studies will produce valuable information about the overall results now being achieved.

An alternative to the comparative field studies approach of the USBR is a mathematical modeling of the scheduling process. It was this approach that was taken in the present study. The requirements of a modeling approach are, first, that the irrigation practices of farmers not using a scheduling service must be characterized in an empirical way; second, that the irrigation practices of farmers who do use such a service must be characterized; third, that the inter-relationship between these irrigation practices and the various parameters of interest (water use, water quality, and income) must be established. With such information at hand, the regional totals of the parameters of interest can be estimated first for farms not using a scheduling service, and again for the same farms based upon use of a scheduling service. The difference in the respective totals can be attributed to the use of the scheduling service.

The benefits of an irrigation scheduling service naturally depend upon the quality of the service and the willingness of farmers to follow its recommendations. The quality of a scheduling service is strongly dependent upon the training, experience and motivation of service personnel (Jensen 1975; Lord, 1976). The willingness of farmers to follow recommendations of the service depends on their motivation, the degree of confidence which they have in the service and their ability to actually implement service recommendations. Other farm operations may interfere with irrigation schedules, water deliveries may not be possible on a recommended date and other factors

may make recommended irrigations unacceptable to a farmer. In light of these considerations, an analysis of irrigation scheduling should consider the consequences of imperfect scheduling. The word "imperfect" here denotes a scheduling operation in which theoretically optimum schedules are not followed. Imperfect operations may be due to poor performance on the part of a scheduling service or failure or the inability of farmers to implement recommended schedules.

A modeling approach will reveal which factors are most important to the success of a scheduling operation and it permits a close examination of the ways in which irrigation scheduling influences non-point-source pollution. It also enables one to study the impacts of irrigation scheduling procedures that are not actually found in current practice but may be of some future value. Finally, the modeling approach has the advantage of speed. Rather than waiting for many years to find out what changes will occur in regional water use, water quality and income as a result of irrigation scheduling under a variety of economic and environmental conditions, these changes can be estimated quickly.

This approach is only as reliable as the models used in the analysis. Models selected for use in the study were as sophisticated as practical and were calibrated when possible with local field data. Conclusions drawn from this research were based on differences between model estimates, thus model biases would be minimized.

The specific objectives of this research were to:

- a. develop a method of assessing the regional environmental and economic benefits and costs of an irrigation scheduling service,
- b. apply that method to a case study for purposes of evaluating the method and developing some perspective on the factors which affect the benefits and costs of a scheduling service,
- c. develop some appreciation for the ultimate potential of irrigation scheduling by evaluating two different scheduling services in a real world setting, one being an imperfectly implemented scheduling service and the other being an ideal scheduling service.

The results of this research should be of particular interest to those policy makers concerned with the question of whether scheduling services are economically justified and, if so, how they can best be implemented and financed. In addition, private companies and government agencies which provide scheduling services to farmers will gain an improved understanding of those factors which determine the benefits to be derived from the service, and the factors which influence the effectiveness of a scheduling service. The study focuses on benefits and costs associated with crop yields, water use, and irrigation return flows.

SECTION 2

CONCLUSIONS

This discussion of conclusions is in two parts. The first five items relate to the impacts estimated for an irrigation scheduling service operating in the A and B Irrigation District of Southern Idaho. Subsequent items describe the techniques that were used in this analysis and the problems encountered in applying them. The conclusions which pertain to the A and B District can be regarded as somewhat general, that is the A and B District should be a good indicator of what to expect from other irrigation districts since irrigation efficiencies are relatively high, and irrigation costs are moderate. In districts where water use is particularly inefficient, or water costs are high, the benefits attributed to irrigation scheduling would probably be greater than those described below. In exceptionally efficient districts, the converse would probably be true.

1. General - Although the A and B Irrigation District's average water use is relatively efficient, there is substantial variability in the scheduling practices of individual farmers. Both timing and quantity of irrigation applications varied tremendously in the fields involved in this study. An irrigation scheduling service operating in the district could produce important environmental and economic benefits. Those benefits would vary substantially from one farmer to another and, to a lesser extent, from one crop to another.
2. Economic Benefits - Although irrigation costs in the A and B District are not particularly high, the potential reduction in irrigation costs due to use of an irrigation scheduling service would pay the cost of such a service in most instances. Improved yields are also possible; the analysis produced some indication that yield improvements might be realized with a scheduling service, and the returns attributed to such increased yields could exceed the cost of the scheduling service. Data problems and yield variability were so great, however, that estimates of yield changes can only be regarded as indicative rather than conclusive.
3. Environmental Benefits - Substantial reductions in total water use and deep percolation could be brought about with the use of an irrigation scheduling service. Somewhat less surface runoff would also occur. These changes would result in reduced salinity and sediment loads in return flows. Estimated return flow changes with irrigation scheduling in the A and B

District included up to 77 percent reduction in deep percolation, 31 percent reduction in surface runoff, 33 percent reduction in TDS loads, and 24 percent reduction in sediment loads. The reduced total dissolved solids (TDS) loads would be accompanied by a shift toward a higher sodium adsorption ratio and lower alkalinity in return flows. The reduced sediment load could be accompanied by corresponding reductions in pesticide and nutrient levels in return flows.

4. Imperfect Scheduling - The potential benefits of a scheduling service can be largely nullified by deviations from the prescribed irrigation schedule in terms of timing and quantity of water applied. As noted earlier, such errors could be due to imperfect knowledge on the part of the service or to an inability or unwillingness of farmers to implement recommended schedules. The environmental benefits mentioned above would be largely offset by such errors. Soil moisture conditions when using scheduling could conceivably be even less favorable to crop production than without a scheduling service. For example, it was estimated that average season total evapotranspiration could be less in a few cases when imperfect scheduling is used than when no scheduling service is used. Since evapotranspiration is a direct indicator of yields, it appears possible that potential improvements in yields due to irrigation scheduling could be offset to some extent by imperfections in the scheduling procedures.
5. Demand - The acreage of scheduled irrigation activity was found to be fairly sensitive to varying scheduling costs. At zero cost, approximately 70 percent of the irrigated cropland in the A and B District would be scheduled but a \$5.00 charge per acre (\$12.36/ha) would reduce scheduling to approximately 25 percent of the acreage. The amount of water use was also affected by changes in scheduling costs. At zero scheduling cost, water use would approximate 75 percent of the water use in the A and B District without a scheduling service and approximate 95 percent when the scheduling costs was raised to \$5.00 per acre (\$12.36/ha). The amount of scheduling increased and the amount of water use and return flows were substantially reduced as water costs were increased. As water costs approach \$20.00 per acre foot, ($\$24.46/10^3\text{cm}^3$) virtually all of the district would employ the scheduling service to reduce the amount of water applied.
6. Analysis of Irrigation Water Use Under Field Conditions - Two general observations can be made regarding analysis of irrigation water use. First, the variability of field data is substantial and it is often difficult to do much

more than model average values and the variability of some factors. Crop yields and surface runoff were two factors which were found to be particularly erratic. The scatter in the data appeared to be due to the fact that some very unpredictable inputs had very significant effects. For example, farmers may intervene to adjust surface runoff from time to time, making it difficult to predict this quantity. Thus, probabilistic modeling is likely to be of paramount importance in modeling irrigation water use. Second, some of the most important relationships are not understood sufficiently well to be modeled accurately under field conditions. Notable examples are crop development and root zone expansion.

7. Estimating Evapotranspiration - Great care must be taken in modeling evapotranspiration since this proved to be the most important single element of the study. Care must be taken to use an evapotranspiration model that is appropriate for local conditions, and to be sure that the crop coefficients used in estimating ET are consistent with the potential evapotranspiration model that is being used.
8. Modeling Soil Moisture - In order to arrive at reasonably accurate estimates of deep percolation and leaching fractions, it is necessary to use a model of soil drainage which accounts for soil moisture conditions both above and below nominal field capacity. In addition, a major effort should be made to accurately estimate effective root depths. Although the results of the analysis were not especially sensitive to moderate errors in root depth, there is a possibility of extremely large errors in this quantity making it one of the more critical factors in the models.
9. Modeling Crop Production - Unexplained yield variability can be very great. Consequently yield estimates must be calibrated for each field on an individual basis if unbiased crop production models are to be developed.

SECTION 3

RECOMMENDATIONS

1. Irrigation scheduling services should be promoted by water quality agencies to reduce the amount of return flows in most irrigated areas of the west.
2. Irrigation scheduling services should be recommended to water agencies to reduce water diversions and pumping for crop production.

SECTION 4

ANALYTICAL SYSTEM

The analytical system is composed of the physical analytical subsystem and a regional economic model (Figure 1). The physical analytical subsystem estimates crop yields, irrigation water use, frequency of irrigation and salt and sediment loads of return flows on a per acre (ha) basis. This information is used by the regional economic model to estimate changes in regional farm income, water use, scheduled acres (hectares) and the amount and quality of irrigation return flows that could result from the use of a irrigation scheduling service.

The physical analytical subsystem is composed of the soil moisture, irrigation, salinity, sediment and crop production models. The soil moisture model estimates evapotranspiration (ET) and soil moisture on a daily basis. These estimates are used by the crop production model to estimate crop yields and by the irrigation model to establish when subsequent irrigations are required. The irrigation model determines irrigation timing and the amount of water to be applied, which is used by the crop production, soil moisture and regional economic models. The irrigation model also estimates the amounts of runoff and deep percolation. These estimates are then used by the sediment and salinity models.

The soil moisture model estimates daily soil moisture by computing a water budget for the crop root zone. The extent of the root zone is determined by a submodel of root growth. Depletion of soil moisture is estimated by submodels of evapotranspiration and deep percolation. The evapotranspiration submodel accounts for bare soil surface, wet soil surface and dry soil profile conditions. Soils in the study area are deep, well drained and sufficiently similar so no provisions were made for upward or lateral soil water movement.

The irrigation model was used to simulate scheduling of fields and the consequences of irrigation applications under the scheduled regimes. The model determines the proper timing of each irrigation event on the basis of the amount of moisture remaining in the root zone. When an irrigation is called for, the model specifies the amount of water to be diverted, calculates losses in the distribution system and generates an estimate of surface runoff. The balance of each simulated diversion is then added to the soil water budget either to be stored in the soil profile or ultimately to drain beyond the root zone. In scheduling irrigations, the model follows essentially the same decision rules used by a scheduling service presently operating in the district. The model can simulate either an ideal scheduling

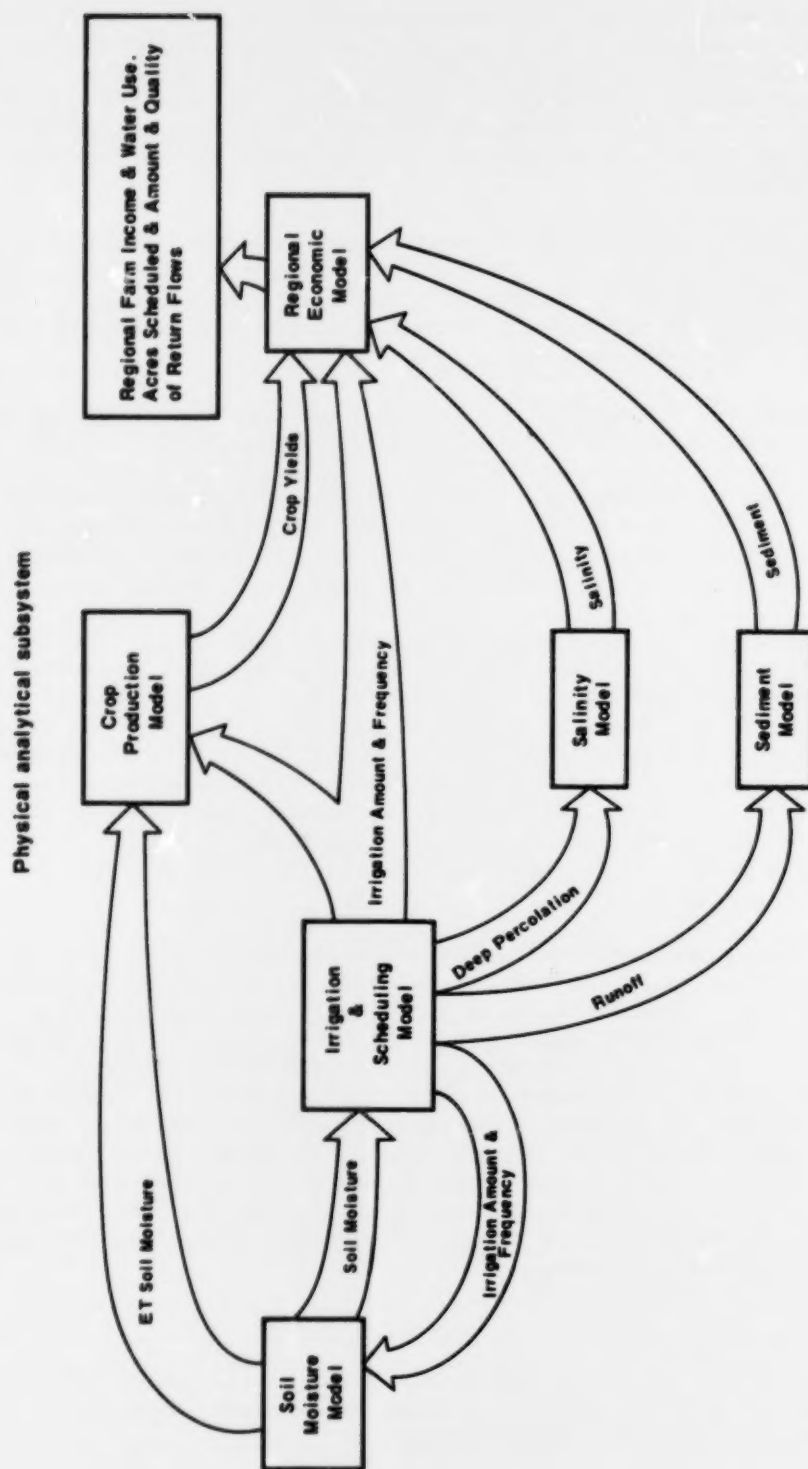


FIGURE 1. Irrigation scheduling analytical system.

operation, in which each irrigation event is presumed to be in accord with scheduling service recommendations, or an imperfect scheduling operation. The imperfect operation is simulated by introducing random deviations from specified dates and amounts of scheduled irrigations. The statistical characteristics of the random errors generated in this model were estimated from earlier observations of such errors by the USBR in actual field operations of scheduling services.

The salinity model predicts TDS concentrations in water percolating beyond the root zone on the basis of the chemical composition of applied water and seasonal leaching fraction. Estimated total salt load in deep percolation is then calculated as the product of estimated TDS concentration and estimated volume of deep percolation.

Regression analysis was used to predict sediment concentrations in surface runoff as a function of the rank* of each irrigation event and the volume of water applied per unit of land area. Certainly many other factors influence erosion and an attempt was made to develop a more sophisticated model that would account for some of the more obvious factors. However, that effort was largely unproductive. Nevertheless, this model was deemed adequate for the purposes of this analysis, as will be explained later.

The crop production or yield model was based in part on known relationships between water use and yields. Yields are adversely affected when either too little or too much water is applied to a crop, and these adverse effects are related to the stage of growth of the crop. A model was developed that would take these principals into account. The model was founded upon a yield-evapotranspiration relationship since the link between these parameters is well established. A stepwise regression procedure was then used to identify other water-related factors which might be useful in predicting yields such as the total water applied and the soil moisture at critical stages of growth.

Crop yield, water use and return flow coefficients for each crop were derived by the physical analytical subsystem under scheduled and unscheduled irrigation operations. These data, crop production costs and commodity prices were used in formulating the regional economic model to determine the amount of water use and type of irrigation system that maximizes regional net farm income. Subsequent runs of the economic model were made to estimate the changes in incomes, water use, scheduled acres (hectares) and return flows that result from varying scheduling costs, water costs and environmental policies. The present research did not deal with specific dollar values associated with changes in water quality, but did yield considerable insight into the relationships between irrigation scheduling and the quality of irrigation return flows.

*Rank refers to the number of event, e.g., the first, second or third event for a given field in a given season would have a rank of one, two or three, respectively.

SECTION 5

STUDY AREA AND DATA BASE

STUDY AREA

The analysis was a case study involving the A and B Irrigation District, a 76,800 acre (31,104 hectare) district located on the Snake River near Burley in southern Idaho (Figure 2). An irrigation scheduling service has been in use there for ten years. Earlier study indicated that utilization of that service may increase local yields of some crops (USBR, 1974). As far as the environmental consequences of irrigation in the area are concerned, there is little problem with salinity in return flows but sediment from erosion is a major problem. The principal reasons for choosing the A and B District were, first, that the area is relatively homogeneous in physical characteristics which simplified the analysis, and second, that a great deal of necessary data and other research have already been compiled by various agencies in the area.

The district is supplied with water pumped both from the Snake River and from wells, with a lift of approximately 200 feet (61 meters) in either case.

One important characteristic of farmers in the A and B District is that even without the benefit of an irrigation scheduling service their irrigation operations are relatively efficient for surface irrigation systems in southern Idaho. It was estimated in this study that distribution system losses were approximately 10 percent of water delivered to the farm while surface runoff and deep percolation account for 39 percent of water applied to the fields. During the ten year period from 1958 to 1968, A and B District deliveries averaged 3.18 acre feet ($3.92 \times 10^3 \text{ cm}^3$) per acre which was considerably less than the 4.1 and 5.09 acre feet per acre (5.06×10^3 and $6.28 \times 10^3 \text{ cm}^3$) in two adjacent districts.

DATA BASE

The analytical procedure developed for this project required both field data and simulation modeling. This work was made easier by the fact that the study area has been the scene of extensive research pertaining to irrigated agriculture. The results of that research were incorporated into the simulation models and analytical procedures of the present study. The shaded area in Figure 3, designated roman numeral I, encompasses six farms (approximately 600 acres) which participated in a USBR study of irrigation water use between 1964 and 1968 (USBR, 1971). An exhaustive data collection



FIGURE 2. Location of the A and B District, Idaho.

program was conducted in each field (maximum number of fields in any one year was 47; number varied from year to year) during each of those years. The data included climatic variables, soil conditions and agronomic and irrigation practices.

Climatic data included daily temperature, humidity, wind, rainfall and solar radiation. Soil moisture and salinity at the beginning of the season were also recorded. The dates of all cultivation, planting and harvesting were recorded along with crop acreages, amounts of fertilizer and pesticide use, and crop yields, losses and quality. Irrigation data included irrigation water quality, amount of distribution system losses, irrigation methods used, field length, slope, row spacing, dates of irrigation, time per set, rate of delivery, labor requirement, infiltration rate, rate of advance and surface runoff. (For a description of this subarea, an outline of USBR research methods and a summary of the data, see Use of Water on Federal Irrigation Projects, USBR, 1971.) These data were collected for 204 cases, each case representing one of the fields during one growing season. This data set is referred to in the present report as the six-farm study.

The areas designated by roman numeral II in Figure 3 represent 4,340 acres (1,756 hectares) encompassing 40 farms, which participated in an earlier interagency study (1958-1963) similar to the six-farm study (Tyler, et al., 1964). The goal of the earlier study was the evaluation of irrigation water use and efficiencies. Data collected on these 40 farms included water deliveries, runoff, weather data and crop yields. However, the data collection effort during the 40-farm study was neither as comprehensive nor as complete as that of the six-farm study.

Another important resource available to the present study was the USDA-SEA Snake River Conservation Research Center, located at Kimberly, Idaho, 40 miles (64 km) west of the A and B District. The soil moisture and evapotranspiration (ET) models used in this project were developed in large part by researchers at that facility who have been working with the same crops, soil and climate as are found in the A and B District.

The University of Idaho maintains experiment stations at Kimberly and at Aberdeen, 80 miles (129 km) east of the A and B District. Research at these stations and comments and suggestions from University of Idaho researchers located there and elsewhere in Idaho also provided a great deal of needed information, on the subjects of farm practices, crop production and erosion.

In addition to the data collected during the six-farm study, the USBR offices in Burley, Idaho (adjacent to the A and B District), Boise, Idaho, and Denver, Colorado, also provided insight and detailed information concerning scheduling procedures, the performance of the USBR scheduling service and irrigation practices and other habits of farmers in and around the A and B District.

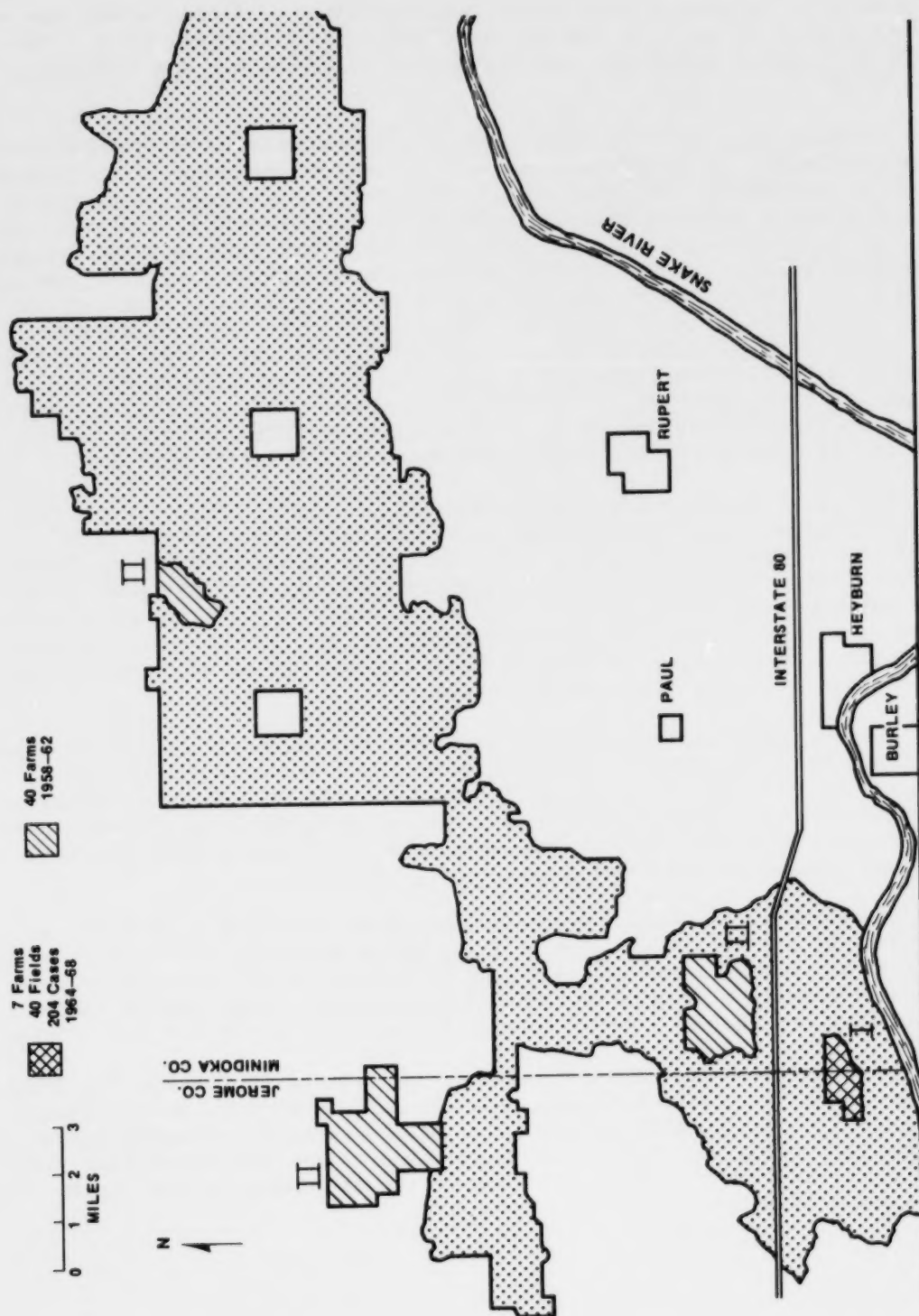


FIGURE 3. Map of the A and B Irrigation District, Idaho.

SECTION 6

PHYSICAL ANALYTICAL SUBSYSTEMS

The environmental and economic impacts that would occur on all farms in the region were inferred from results observed on the 46 farms which participated in the studies described above. The analysis took place in two phases. In the first phase, data collected from the sample farms were used to establish relationships between irrigation practices, crop yields, and the amount and quality of return flows. Also, the irrigation practices of farmers in the region were studied and characterized for each crop. The information and relationships developed in the first phase were then combined to establish coefficients for a regional economic linear programming model used in the second phase. The linear programming model determined optimum water use and utilization of a scheduling service under three different irrigation regimes and a variety of scheduling and water costs.

The three irrigation regimes differed in how the irrigation water was managed. The three regimes are unscheduled, ideal scheduling, and imperfect scheduling. Under the unscheduled regime farmers are assumed to be irrigating using their own judgment of crop water needs. An ideal scheduling regime is presumed to have perfect knowledge of soil moisture conditions in every field at all times and, furthermore, each farmer is presumed to irrigate his fields precisely when advised to do so, using exactly the recommended amount of water. The imperfect scheduling regime assumes that errors occur in both the timing and amount of irrigations, which is currently the rule rather than the exception in irrigation scheduling operations.

SOIL MOISTURE MODEL

The soil moisture model estimates evapotranspiration (ET) and soil moisture for each crop by calculating soil moisture budgets for the active root zone and a lower zone into which the root system will eventually move.

Soil Moisture Holding Capacities

On the basis of field data from several sources, the moisture holding capacities of soils in the study area were assumed to be:

1. 37 percent by volume* on the day following a thorough irrigation;
2. 30.7 percent by volume at the limit of gravity drainage; and
3. 10 percent by volume at the limit of extraction for evapotranspiration (15 bars tension assumed).

The soil was assumed homogeneous with respect to these capacities throughout the study area. However, this assumption is only an approximation, the validity of which may be judged by the variability in gravimetric analyses of five soil samples taken from different sites in the study area. These are presented in Table 1. The values shown are composite values of samples taken at a depth of from 10 to 150 cm. The standard deviation of the soil moisture content at one-third bar tension is 6 percent of the mean.

TABLE 1. MOISTURE HOLDING CAPACITIES (% BY VOLUME) OF FIVE SOIL SAMPLES TAKEN IN THE UPPER 150 CM OF SOIL PROFILE IN THE STUDY AREA

	Sample Number					Mean $\pm$	Std. Dev.
	1	2	3	4	5		
Moisture content, 1/3 bar	27.32	28.56	32.26	29.47	28.98*	29.32 $\pm$	1.83
Moisture content, 15 bar	8.74	9.32	9.83	8.06	8.32*	8.85 $\pm$	0.72
Bulk density, gm/cm ³	1.38	1.40	1.41	1.39	--	1.40 $\pm$	0.01

*Mean value of bulk density used to compute values.

The model computes the soil moisture budgets as follows. When water is applied at the soil surface it is added to the moisture budget of the current root zone until the limit of capacity (37%) is reached. Any additional water infiltrating the soil will be added to the budget of the lower portion of the root zone. When the limit of capacity of the lower root zone is reached additional water is assumed to percolate beyond the maximum root zone. When the soil moisture is between 10 percent and 30.7 percent, depletion will take place only through evapotranspiration. When the moisture level is between 30.7 percent and 37 percent, depletion taking place by both evapotranspiration and percolation processes is simulated by the model.

*Throughout this report, where soil moisture is expressed as a percent it refers to percent by volume.

Estimates of percolation and soil moisture content can be significantly affected by large errors in the value of the maximum moisture holding capacity used in the soil moisture model. In fact, a dominant impression to come from this study has been the importance of properly modeling soil moisture at levels above nominal field capacity. Otherwise, substantial errors in computation of leaching fractions and soil moisture budgets may result. The model therefore estimates both ET and percolation simultaneously at soil moisture levels above field capacity.

Root Zone Depth

The estimation of evapotranspiration and percolation also depend on the size of the active root zone. The active zone increases with the growth of the crop. Jensen developed a root zone model that relates root zone size to the crop growth stage (M. E. Jensen, personal communication, 1979). The equations of this model are:

$$L(t) = (Z_m - 15) \cdot k_{co}(t) + 15 \quad t \leq \text{full cover date} \quad (1)$$

$$L(t) = Z_m \quad t > \text{full cover date} \quad (2)$$

where

$L(t)$ = root zone depth at time t , in centimeters (cm),

Z_m = maximum root zone depth for the given crop,

$k_{co}(t)$ = crop coefficient used in the evapotranspiration equation (to be discussed below)

This model has been used by the USBR in its Irrigation Management Services (IMS) program.

The following are assumed effective maximum root zones used for the various crops (Z_m). They were derived from Doorenbos and Pruitt (1975), Hagan et al., (1967) and Hansen (1972).

<u>Crop</u>	<u>Maximum Root Zone in Cm</u>
Alfalfa	213
Barley	91
Beans	61
Peas	91
Potatoes	61
Wheat	91
Sugar Beets	76

The values shown are not absolute maximum root zones. Rather, they are estimates of the depths from which most of the water will be drawn by the

crops under normal circumstances. Under stress conditions, these crops might tap water from greater depths. For example, sugar beet roots may extract water down to 180 cm (M. E. Jensen, personal communication, 1979; University of California, 1976) and beans in some circumstances may reach depths of from 183 to 274 cm (from field studies, University of California at Davis, Summer 1977; Juan Tosso, personal communication).

Deeper root zones, had they been used in the model, would have resulted in fewer irrigations and greater pre-season soil moisture availability. Under these circumstances, the evaluation of irrigation scheduling would have been more favorable. The shallower root zones are deliberately selected to avoid biases that would attribute unattainable benefits to scheduling. Equally important, these shallower root zones are consistent with the somewhat conservative estimates of root zones which scheduling services generally use in selecting allowable soil moisture depletions between irrigations.

There remains a question of whether actual effective root zones might be shallower than the values used. This possibility was suggested because local soils are underlain by a moderately cemented layer between approximately 46 and 91 cm. below the surface which might be a barrier to root development.

Kohl and Kolar (1976) found that alfalfa grown in this soil was able to penetrate the cemented layer and develop an extensive root system below it. However, there was no assurance that this would be true of other shallower rooted crops. A bean field in the A and B District was studied by the authors during the summer of 1977. Twenty-five neutron probes were installed throughout a section of the field and soil water extraction by the crop was measured to a depth of 91 cm. A fungus which occurs in this area (*Fusarium* root rot) commonly attacks the tap root of beans, sometimes destroying it within 15 cm. of the surface (McMaster, et al., 1965), so this crop could be expected to have more difficulty penetrating the cemented layer to a significant extent than would other crops. However, it was found that soil water extraction in the upper 91 cm. accounted for less than half of the consumptive use estimated by a locally calibrated Penman ET model. The bean crop was obviously growing well and not suffering significant stress. It was concluded that in spite of the problems presented by this soil, the root zones used in the study are reasonable.

The degree of uncertainty of root depths is very great, as may be illustrated by the following ranges of published root depths (Doorenbos and Pruitt, 1975; Hagan et al., 1967; Hansen, 1972; Nielsen et al., 1973; M. E. Jensen, Personal Communication, 1976).

<u>Crop</u>	<u>Maximum Root Zone Depth in Cm</u>
Alfalfa	90 to 360
Beans	45 to 900
Sugar Beets	60 to 120
Grains	60 to 120

It appears that large errors in estimation of root development may be difficult to avoid and therefore this must be regarded as one of the critical factors in the model. Root depths used in the analysis were conservative estimates, i.e., probably shallower than is actually the case. This would lead to conservative estimates of any benefits that might result from the use of scheduling.

A sensitivity analysis was conducted to assess the significance of errors in root depth estimates. Percolation was found to be sensitive to root depths, while consumptive use was found to be rather insensitive. For example, in the ten representative fields used in the sensitivity analysis, a 20 percent increase in root depths caused a 10 percent decrease in percolation and a 1.0 percent increase in ET under the unscheduled irrigation regime.

Soil Drainage Submodel

The rate of percolation is computed by the following function of soil moisture and root zone depth:

$$J = B_0(L) + B_1(L) \cdot (\theta_o - \theta) + B_2(L) \cdot (\theta_o - \theta)^2 + B_3(L) \cdot (\theta_o - \theta)^3 \quad (3)$$

$$\text{in which } B_1(L) = \sum_{k=0}^3 a_{1k} \cdot L^k \quad (4)$$

where

- J = rate of drainage, in cm per day, from the root zone,
- L = depth of the root zone, in cm,
- θ_o = maximum soil moisture (37% by volume)
- θ = current soil moisture, expressed as percent by volume
- $B_1(L)$ = a coefficient dependent upon depth L, in cm
- a_{1k} = coefficients used in calculating B_1 .

In deriving these equations, polynomial regressions were used to fit a family of soil moisture drainage curves generated by a theoretical model calibrated with experimental data for Portneuf silt-loam soil in Kimberly, Idaho. The soil drainage model estimates drainage rate from a soil profile of depth L and moisture content θ . If hydraulic conductivity is taken to be an exponential function of soil water content of the form:

$$k(\theta) = K_o \exp [\alpha(\theta - \theta_o)]$$

where

- K_o = conductivity under conditions of steady state infiltration rate,
 θ_o = soil moisture content under conditions of steady state infiltration rate,
 α = a constant,

then flux and soil moisture can be estimated as the following functions of time (Nielsen, et al., 1973):

$$J = \frac{K_o}{1 + \frac{\alpha K_o t}{L}} \quad (5)$$

$$\theta = \theta_o - \frac{1}{\alpha} \ln \left(1 + \frac{\alpha K_o t}{L} \right) \quad (6)$$

in which

- J = flow rate through the bottom of the soil profile,
 L = depth of soil profile
 t = time (with $t = 0$ at θ_o)

Soil drainage rates were measured by Jensen (personal communication, 1976) at a single site, for Portneuf silt loam soil at depths of 60 cm and 105 cm as indicated by the solid lines in Figure 4. These data were used to calibrate equation 5 for α and K_o . The dashed lines in Figure 4 represent the resulting calculated drainage rates. Equations 5 and 6 were then used to generate paired values of J and soil moisture depletion ($\theta_o - \theta$) for values of t and for L ranging from 10 cm to 2 m. The result was a family of curves, each relating J to ($\theta_o - \theta$) for a specific value of L , as illustrated by the example curves for 60 and 105 cm in Figure 5. A polynomial regression function of the form:

$$J = B_{0L} + B_{1L} (\theta_o - \theta) + B_{2L} (\theta_o - \theta)^2 + B_{3L} (\theta_o - \theta)^3 \quad (7)$$

was derived for each of these curves. The coefficients B_{iL} are unique for each depth L . The set of B_{iL} coefficients for each i were then used with a second polynomial regression to derive an equation for B_i as a function of L :

$$B_i(L) = a_{i0} + a_{i1} L + a_{i2} L^2 + a_{i3} L^3 \quad (8)$$

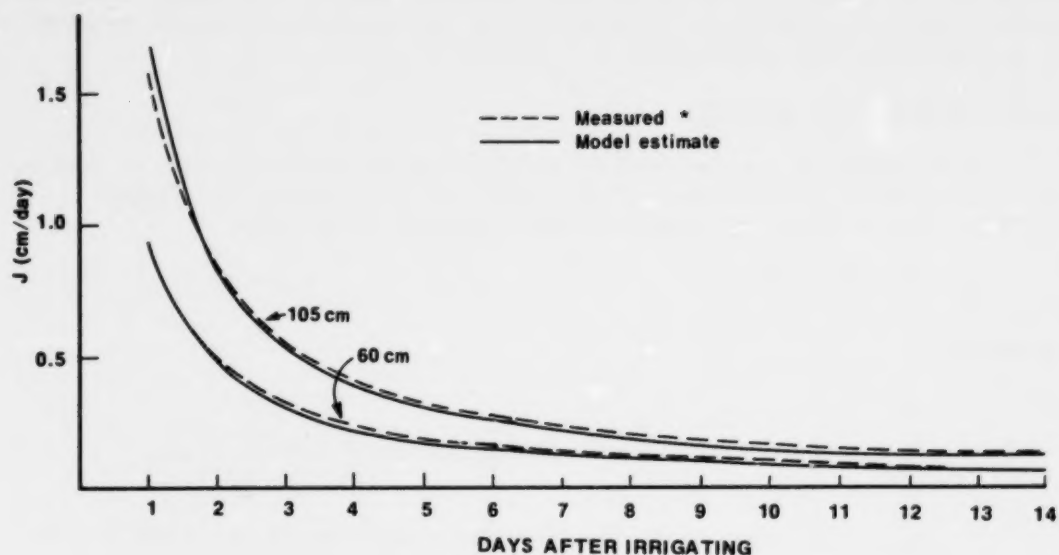


FIGURE 4. Rate of drainage (J) from a 60 cm and 105 cm soil column as a function of time (in days). *Based on Jensen, 1976, personal communication.

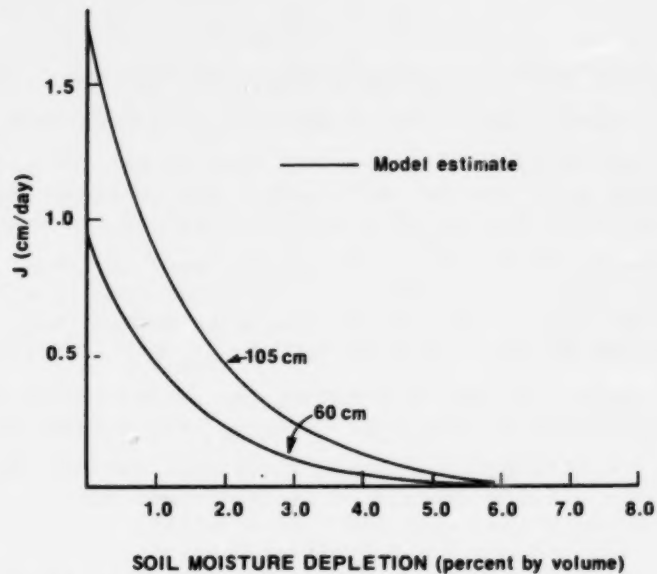


FIGURE 5. Rate of drainage (J) from a 60cm and 105cm soil column as a function of soil moisture depletion.

Soils in the study area are very deep and well drained and there is no water table close to the surface. Therefore, no provisions for upward movement of groundwater were included in the model.

Evapotranspiration Submodel

Calculation of evapotranspiration follows methods proposed by Jensen, et al., (1969). The potential rate (PET) is computed by the Penman equation with a modified wind function. Actual ET is then:

$$ET = k_c \cdot PET \quad (9)$$

in which

$$\begin{aligned} k_c &= k_{co} \cdot K_a + K_s, \\ k_{co} &= \text{crop coefficient (a time dependent coefficient),} \\ k_a &= \ln(M_A + 1) / \ln(10) \\ M_A &= \text{percent available moisture remaining at the time of the estimate,} \\ K_s &= (0.9 - k_{co} \cdot K_a) \cdot 0.8 \text{ on first day after water is applied} \\ &= (0.9 - k_{co} \cdot K_a) \cdot 0.5 \text{ on second day after water is applied} \\ &= (0.9 - k_{co} \cdot K_a) \cdot 0.3 \text{ on third day after water is applied} \\ &= 0 \text{ at all other times} \end{aligned}$$

K_a is an adjustment term for low soil moisture conditions, and K_s adjusts for wet soil surface conditions. The parameter k_{co} is usually defined, somewhat ambiguously, as the ratio of the actual ET rate to the potential rate for a reference crop under well watered conditions. The ambiguity in the definition of k_{co} arises from the meaning of potential rate and the determination of the actual rates from which the crop coefficients were derived. PET may be either the evapotranspiration rate as measured for a reference crop in a lysimeter or the rate calculated by one of the several available models (e.g., Penman or Jensen-Haise). The actual ET rates used to derive k_{co} may or may not include

evaporation from wet soil surfaces during the period immediately following an irrigation or rainfall. For this study k_{co} was defined as the ratio of actual ET, for a well watered crop under dry soil surface conditions, to the potential rate for alfalfa calculated by the Penman equation with a modified wind function and with the vapor saturation deficit calculated as the daily mean of the maximum and minimum deficits. Several requisite crop curves consistent with this definition have been developed at the Snake River Conservation Research Center, 64 km west of the study area. For other published crop curves, it was necessary to make adjustments to account for the methods by which they were derived. In making these adjustments the investigators

were assisted by suggestions from Dr. Marvin Jensen and related research by R.D. Burman (Jensen, 1973). The crop coefficient curves used in the study are presented in Figure 6. The curves presented for sugar beets, grains, peas and beans were developed by McMaster (1976), Ruffing, et al., (1974), Ruffing and Jensen (1976) and Wright and Jensen (1976), respectively. The crop coefficient for potatoes is essentially a compilation of information from local experts and is not from published sources. Using recorded dates for planting, full cover and harvest, the daily crop coefficients k_c were calculated for the entire season for each field. Soil moisture was measured once in each of the 204 cases, early in the season, by the USBR. Soil moisture conditions were initialized for the day on which that measurement took place and soil moisture was calculated daily from that point on. Initially a crop coefficient of 0.1 was used for bare soil evaporation. This resulted in evident errors in estimates of soil moisture, so an empirical soil evaporation model suggested by Jensen (1977) was used for the bare soil case:

$$E = 8.0 e^{-0.139t} \text{ mm/day} \quad (10)$$

in which t is the number of days since the last irrigation or rainfall. The cumulative evaporation calculated by this equation may not exceed the amount of water applied and the daily rate may not go below 1 mm/day. This model was used until the day on which the crop was assumed to have completely emerged. The following emergence dates were selected after consultation with irrigators and irrigation advisory services in the area.

<u>Crop</u>	<u>Time of Emergence in Days</u>
Barley	10
Beans	10
Peas	10
Potatoes	10
Sugar Beets	30
Wheat	10

The soil moisture model was of central importance to this research since this model generated estimates of soil moisture, evapotranspiration and deep percolation. These values were used not only directly in the analysis, but also as inputs to the other models. An evaluation of the sensitivity of model outputs to various input parameters was conducted using data from ten representative fields. As might be expected, it was found that evapotranspiration estimates were of critical importance. However, the ET submodel was developed from the Penman equation and calibrated locally by Wright and Jensen (1972). Furthermore, several of the crop curves as well as the ET adjustment equations were developed by Wright and Jensen under essentially the same conditions of soil, climate and crop varieties. It is therefore reasonable to expect a high degree of accuracy in the ET estimates used in the study.

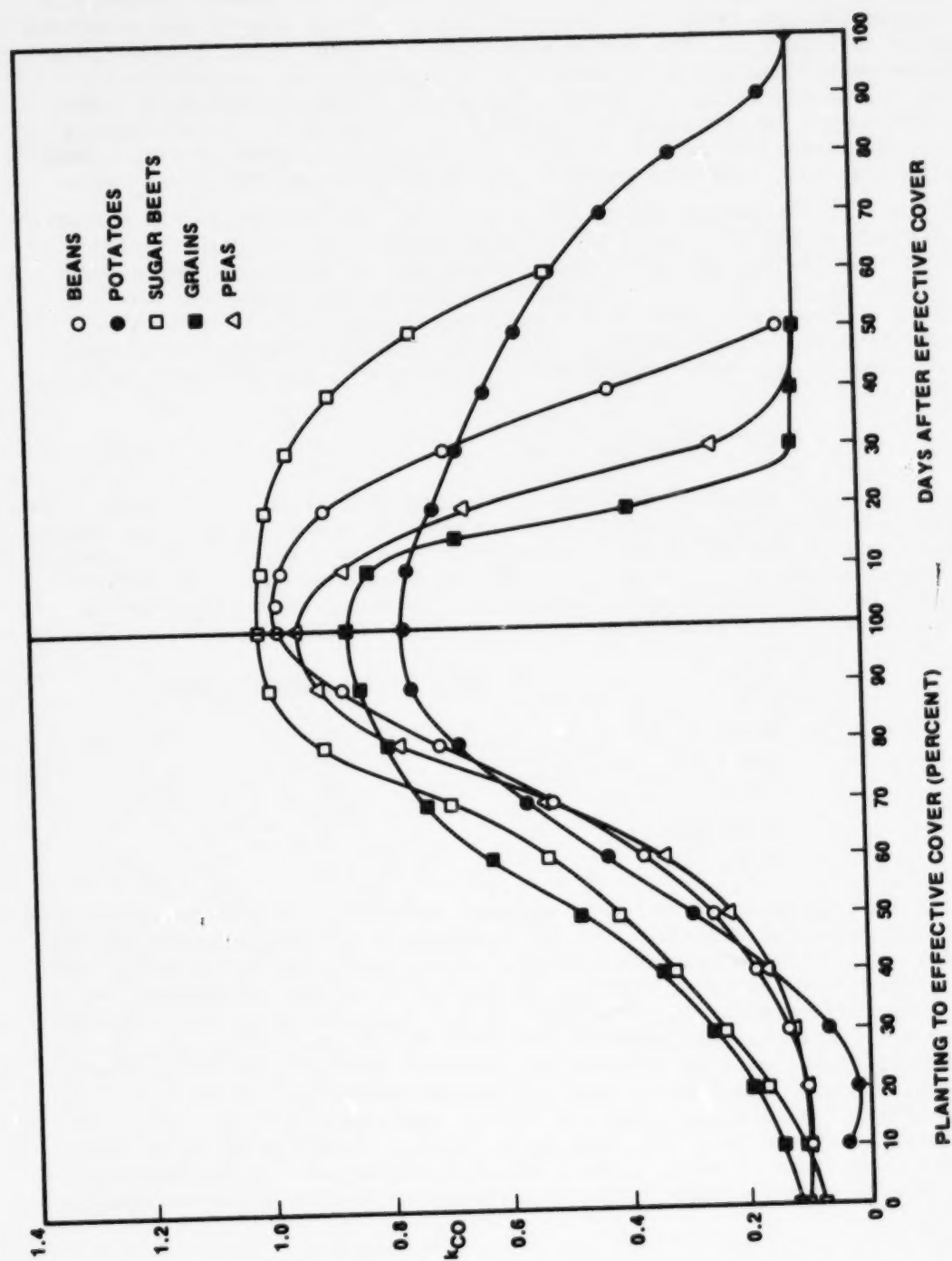


FIGURE 5. Crop coefficient curve for beans, peas, grains, sugar beets and potatoes.

The accuracy of model estimates of evapotranspiration may be judged by comparing the average season total evapotranspiration, as estimated by the model for each of the crops, with total evapotranspiration observed for these same crops under controlled experimental conditions (Table 2). The majority of the experiments were done at Kimberly, Idaho, and therefore involved the same climate and soil type as found in the A and B District.

TABLE 2. COMPARISON OF AVERAGE CONSUMPTIVE USE ESTIMATED FOR THE A AND B DISTRICT AND MEASURED CONSUMPTIVE USE AT VARIOUS SITES

Crop	Average of Model Estimates of ET, A and B District (cm)	Average of Measurement ET, Various Locations (cm)	Absolute Error* (cm)	Hectares in Production in 1977
Alfalfa	87.1	91.7 ^{1/}	-4.6	16039
Barley	43.2	43.2 ^{2/}	0	14965
Beans	39.6	50.0 ^{3/}	-10.4	5860
Potatoes	51.3	59.4 ^{4/}	-8.1	5443
Wheat	43.7	45.7 ^{5/}	-2.0	9567
Beets	63.0	61.7 ^{6/}	+1.3	12026
Peas	35.6 ^{8/}	34.0 ^{7/}	+1.8	1675

*A and B District 1975, Weighted Average Error -3.4%.

^{1/} Measured at Kimberly, Idaho.

^{2/} Estimated by D.T. Westermann from field research at Kimberly, Idaho.

^{3/} Measured at Kimberly, Idaho, 1973, 1974 (J. Wright, personal communication)

^{4/} Measured at Kimberly, Idaho, 1972 (J. Wright, personal communication)

^{5/} Average of values measures at sites in S. Alberta (16.3 in., 18.2 in.) and S. Dakota (19.4 in.).**

^{6/} Measured at Kimberly, Idaho.

^{7/} Measured at site in South Alberta.**

^{8/} Average of values from fields in which alfalfa was not grown simultaneously.

**"Consumptive Use of Water and Irrigation Water Requirements," Irrigation and Drainage Division, Jensen, 1973 (ASCE).

Based on the 1975 cropping pattern for the entire district the model predictions show a weighted average error of -3.8 percent. This slight underestimation may be due in part to the fact that researchers referenced in Table 2 were generally careful to keep their crops well watered, whereas some of the farmers in the A and B District were occasionally observed to let their fields become drier than would be advised. It was concluded that evapotranspiration estimates generated by the soil moisture model are very nearly unbiased, which increases confidence in estimates of changes in

water use and deep percolation that would occur due to irrigation scheduling.

IRRIGATION MODEL

The amount and timing of irrigations for each crop is estimated by the irrigation model. This information is used by the production (yield), soil moisture, and regional economic models.

The irrigation model was used to simulate scheduling of fields and the consequences of irrigation applications under the scheduled regimes. The model determines the proper timing of each irrigation event on the basis of the amount of moisture remaining in the root zone. When an irrigation is called for, it specifies the amount of water to be diverted, calculates losses in the distribution system and generates an estimate of surface runoff. The balance of each simulated diversion is then added to the soil water budget either to be stored in the soil profile or ultimately to drain beyond the root zone. In scheduling irrigations the model follows essentially the same decision rules used by a scheduling service presently operating in the district.

Water Application Submodel

A critical soil moisture level was selected for each of the stages of growth for each crop (Table 3). Whenever soil moisture reached the critical level an irrigation was called for. The amount of water to be applied was calculated by the equation.

$$W_D = \frac{(W_{FC} - W)}{E} \quad (11)$$

in which

- W_{FC} = nominal field capacity in the root zone, in inches,
- W = present soil moisture content, in inches,
- E = overall efficiency of irrigation, including all losses, runoff and percolation,
- W_D = amount of water to be diverted, in inches.

The choice of values for W_{FC} and E could significantly affect the results achieved by a scheduling service (and therefore the estimates produced in this study). The local USBR scheduling service uses an efficiency of 65 percent for surface irrigation systems in the study area, based on calculations of attainable efficiencies. However, USBR personnel felt that 60 percent was more realistic for the efficiencies actually achievable in the area. The lower estimate of efficiency results in a more conservative evaluation of the potential benefits of irrigation scheduling. The value of field capacity, W_{FC} , was taken to be 33.5 percent moisture by volume, which was the moisture level that was usually calculated by the soil moisture model

TABLE 3. SOIL MOISTURE LEVELS AT WHICH SIMULATED IRRIGATIONS WERE SCHEDULED

Crop	Critical Soil Moisture Level (% by volume)	Dates
Alfalfa	20	All season
Barley, Wheat	18	Until 80% cover
	20	Until 20 days after full cover
	16	Until end of season
Beans	18	Until 80% cover
	20	Until end of season
Peas	20	Until 80% cover
	21	Until 10 days after full cover
	20	Until end of season
Potatoes	23	Until full cover
	22	Until end of season
Sugar Beets	20	Until 75% cover
	21	Until end of season

after two or three days of drainage following a thorough irrigation. Note that W_{FC} is not equivalent to the limit of gravity drainage (30.7 percent). Rather it is the soil moisture level which would probably be selected as the field capacity by a scheduling service. Equation 11 was used to determine the need for irrigations under both the ideal and imperfect scheduled regimes. However, under the imperfect regime random errors in the actual timing and amount of each irrigation were then introduced. The submodel that was used to simulate these errors consisted of two random error generators, which simulated random deviations from the specified quantity of water to be applied and random numbers of days difference between recommended and actual irrigation dates. The statistical parameters used for the random error generators were based upon data collected by the USBR from two other locations in which irrigation scheduling is being practiced. One site was the Falls Irrigation District, located approximately 80 km east of the A and B District, near American Falls, Idaho. The other site was the Grand Valley, near Grand Junction, Colorado. In the Falls District the USBR collected data on timing errors in scheduled fields for several different crops (USBR, 1974). The Grand Valley data consisted of observed errors in quantities applied to sugar beet crops by furrow irrigation (Brost, 1977). Seasonal ET in the Falls District is slightly lower than in the A and B District. Based upon USBR estimates of ET in both locations, the difference appears to be on the order of 10 percent. Therefore, the errors simulated by the model would tend to be conservative. The Grand Valley data could not be used directly because there was no assurance that circumstances there were similar to the A and B District. However, the Grand Valley data were used to establish the general shape of the statistical distribution used for the A and B District.

The raw data from these sites are summarized in Figures 7 and 8. Errors in timing were found to range approximately between plus ten and minus ten days for three categories of crops, although the shape of the distributions differ within those limits. (An error on the plus side indicates that an irrigation took place after the recommended date.) Additional data from alfalfa fields were available, but were insufficient for presentation in this graphical form. However, mean and standard deviation of errors for alfalfa was +3.0 days and 6.37 days, respectively.

Application errors in the Grand Valley show a pronounced bias on the positive side, indicating that farmers used considerably more water than was recommended (Figure 8). The expected error in applications was +7.50 cm and the standard deviation was 8.20 cm. The data presented in Figure 8 do not include two extreme valued errors that were observed (+58.2 cm and +66.0 cm). The forms of the statistical distributions of simulated errors for the A and B District were taken from these data.

The distribution of timing errors used in simulation of imperfect scheduling was a composite of the distributions observed for the various crops in the Falls district. The same composite distribution was used for all crops. This approximation was deemed acceptable for purposes of estimating regional average water use, deep percolation, runoff and associated water quality parameters. On the other hand, this approximation could lead to biased estimates of crop yields (as well as crop quality in the case of potatoes) since yields of different crops would be affected differently by timing errors in irrigation scheduling. However, no estimates of yields were made for the imperfect scheduling regime.

The statistical errors in quantity applied were assumed to have the same shape of distribution as the Grand Valley data, but the parameters of the distribution were estimated from A and B District data. The errors observed in the Grand Valley were normalized by dividing them by the average error (7.50 cm). The resulting normalized distribution was then used to simulate errors in the A and B District. Random errors were generated using the normalized distribution, then multiplied by the expected error for the A and B District. A USBR study (1974) of irrigation scheduling in the A and B District estimated that water use on scheduled fields in 1972, actually increased slightly, by a weighted average of 2 percent. From our own initial analysis of 204 cases (to be discussed below), it was estimated that average historical water use was 32.3 percent greater than the ideal quantity. The expected error for any single irrigation was therefore arbitrarily set at 35 percent of the recommended amount. Note, however that this will lead to a conservative estimate of the effects of error in quantity applied. Insofar as scheduling reduces the total number of irrigations, the final estimate of water use under the imperfect regime would still be less than under the unscheduled regime.

The computational procedure for generating errors in quantity applied can be represented by the following equation:

$$Q_A = Q_1 (1.0 + 0.35 (1 + RQ)) \quad (12)$$

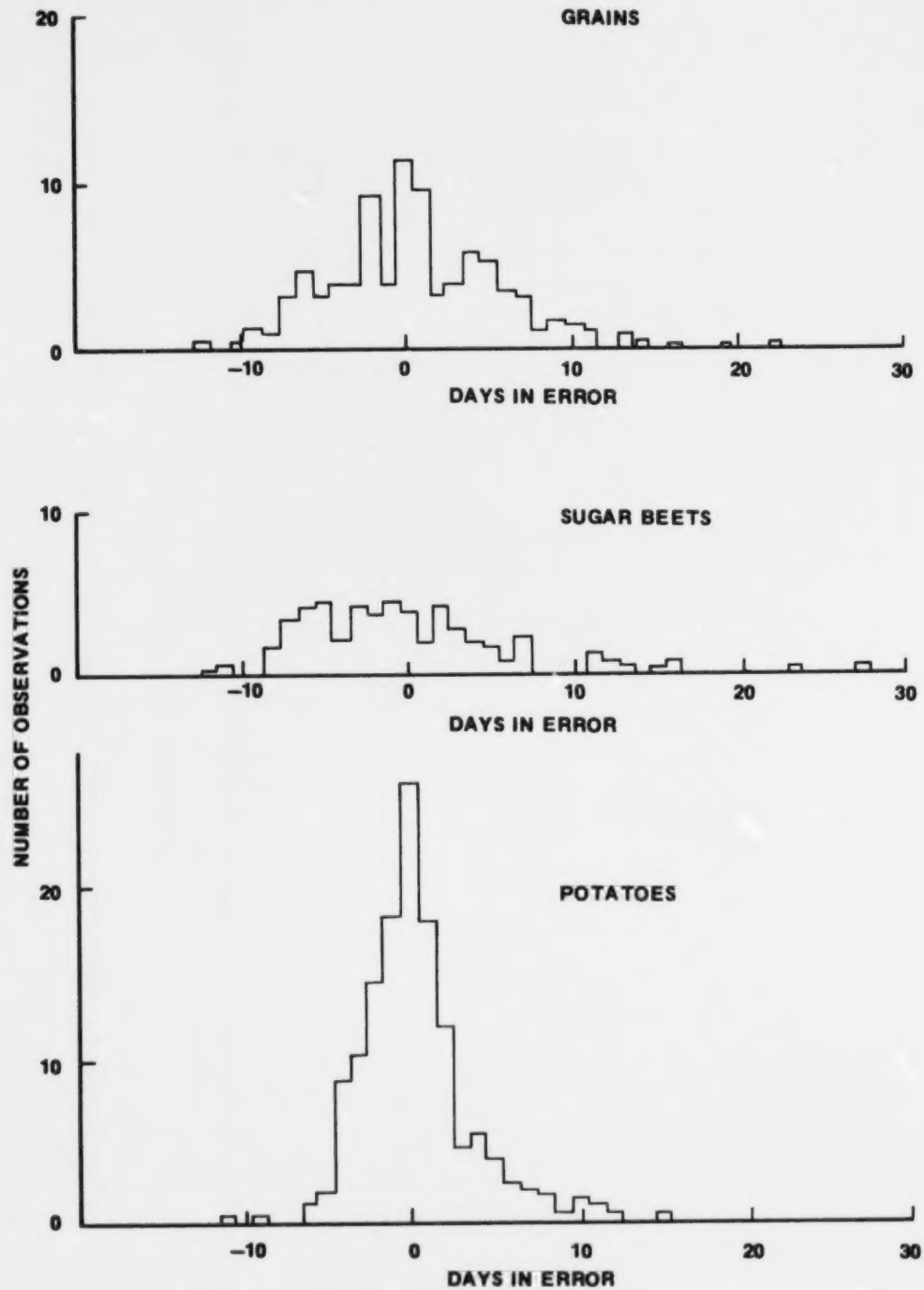


FIGURE 7. Distribution of errors in timing of irrigations, Falls Irrigation District.

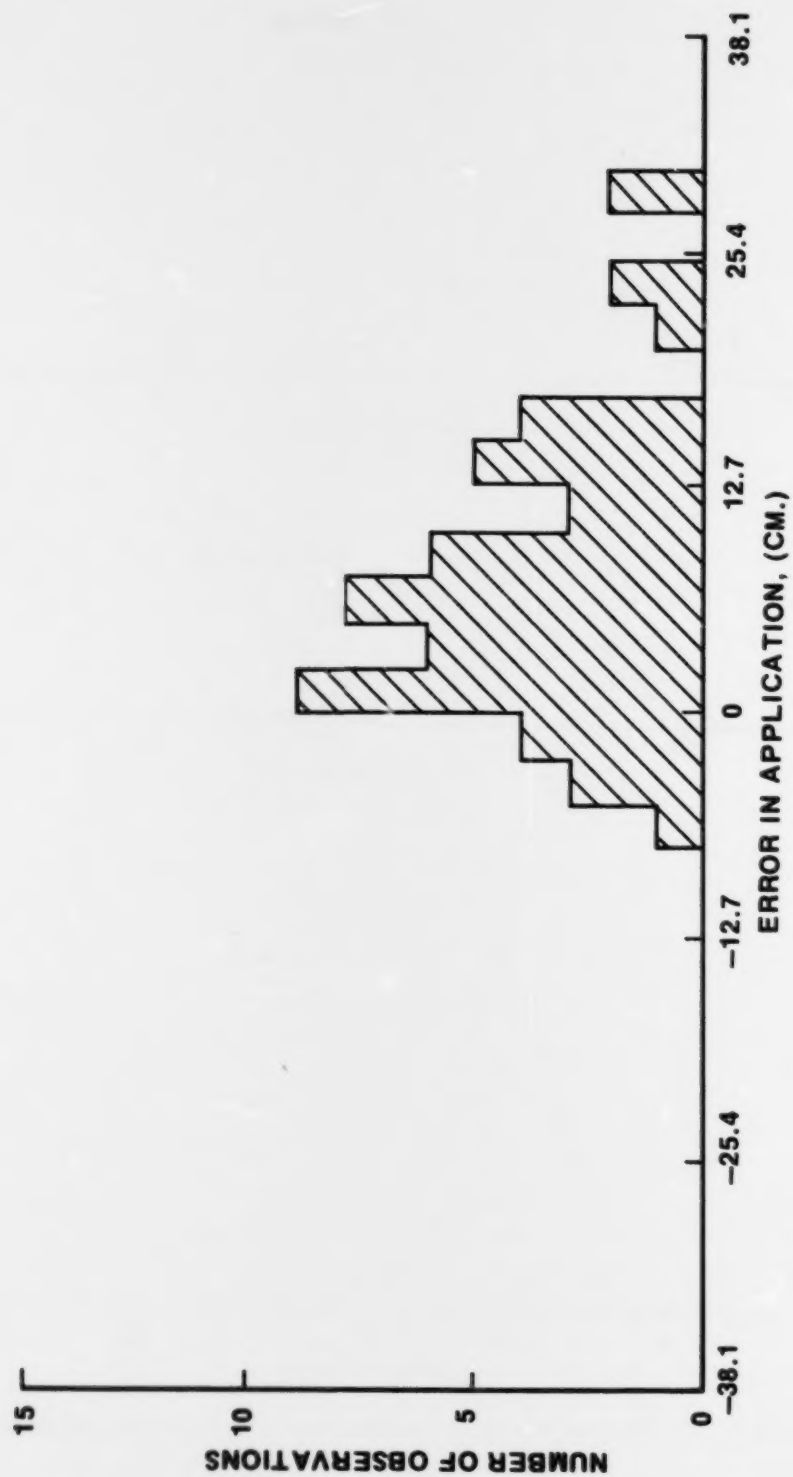


FIGURE 8. Application errors on sugar beets, Grand Valley (cm.).

in which

- Q_A = actual application (cm)
- Q_I = ideal application (cm)
- RQ = normalized error in application (cm/cm)

The statistical distributions of errors in timing and normalized errors in quantity (RQ) used in the model are shown in Figures 9 and 10.

The possibility of correlation between errors in timing and errors in quantity was considered, but Grand Valley data indicated that this might be of little consequence. The Grand Valley data included errors in timing as well as quantity and the coefficient of correlation between these two types of error was 0.11. Consequently, this correlation was not simulated by the irrigation model.

Runoff Submodel

The runoff submodel was developed empirically using data from 1,050 irrigation events that were monitored by the USBR. Runoff was assumed to be determined by: (1) the small scale physical characteristics of the fields, including furrow shape and roughness, vegetative resistance and infiltration rate, (2) the large scale features of slope and length of run, (3) the rate and amount of water application, and (4) the techniques and skills of individual farmers. The slope, length of run, rate of application and amount of water applied were known quantities. The small scale physical features and the farmer's skill were unknown quantities, so it was desired to use some indirect indicator for each of them. The indicators considered were time (starting at planting data and scaled to season length), type of crop and antecedent soil moisture conditions. Time was regarded as a possible index of the influence of vegetative cover and any other time variant factors such as furrow conditions. Crop type was also assumed to reflect vegetative cover, as well as many factors associated with a particular type of crop, such as furrow shape and roughness or rates of application. Antecedent soil moisture condition was assumed to be at least somewhat indicative of average infiltration rate. Total water applied per unit of land area was regarded as a rough indicator of the rate of application since virtually all farmers used the same set times (24 hours). In summary then, the factors considered for the runoff model were crop type, rate of application, quantity of water applied, slope, length of run, antecedent moisture conditions and time (scaled to crop development).

These factors were combined in a stepwise linear regression model. A non-linear least squares fit was also tried. In addition, each factor was plotted individually against runoff to develop a visual impression of the data and to detect any obvious non-linear relationships. Finally, histograms of each factor were plotted to get a better perspective on the significance of the various factors.

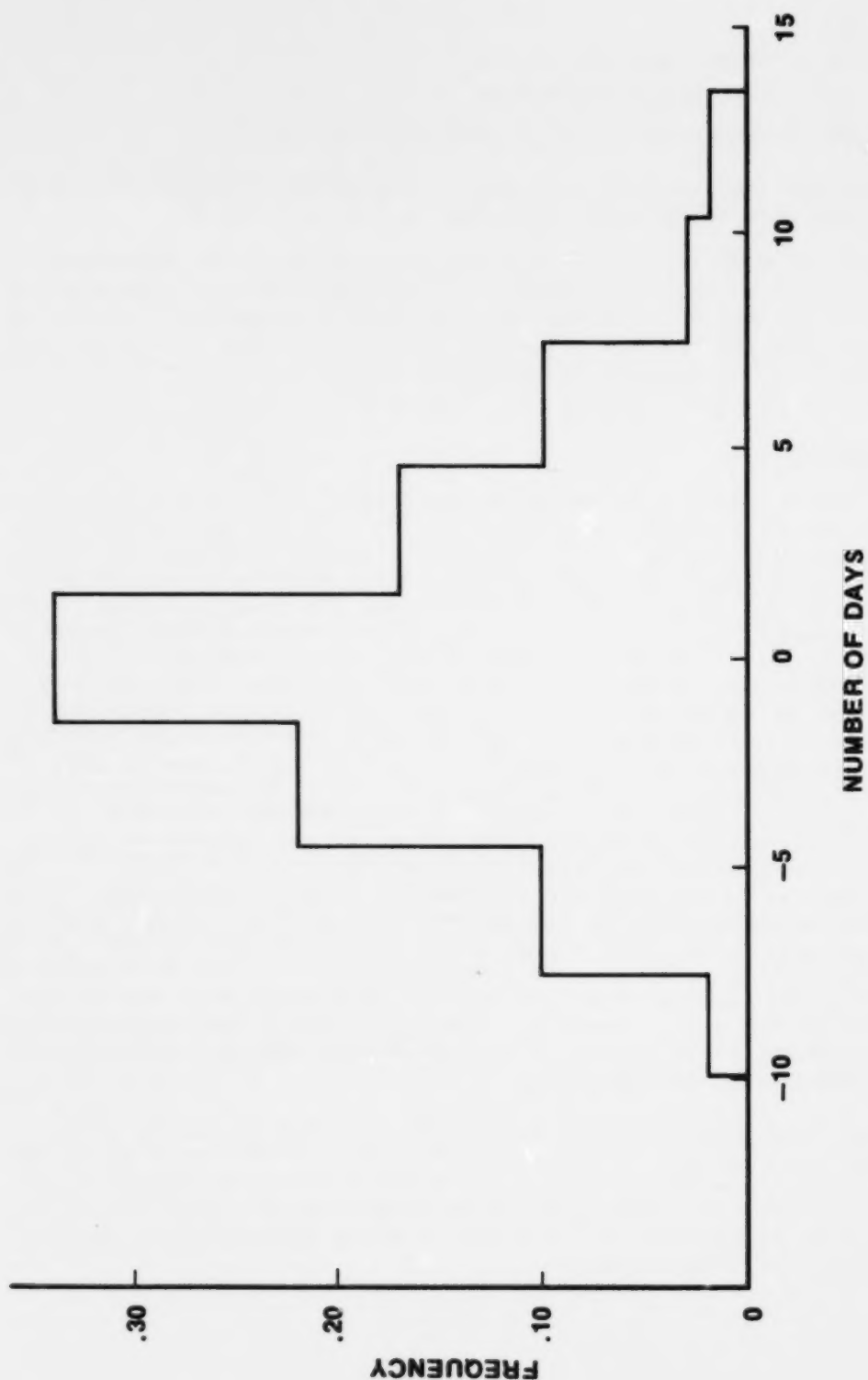
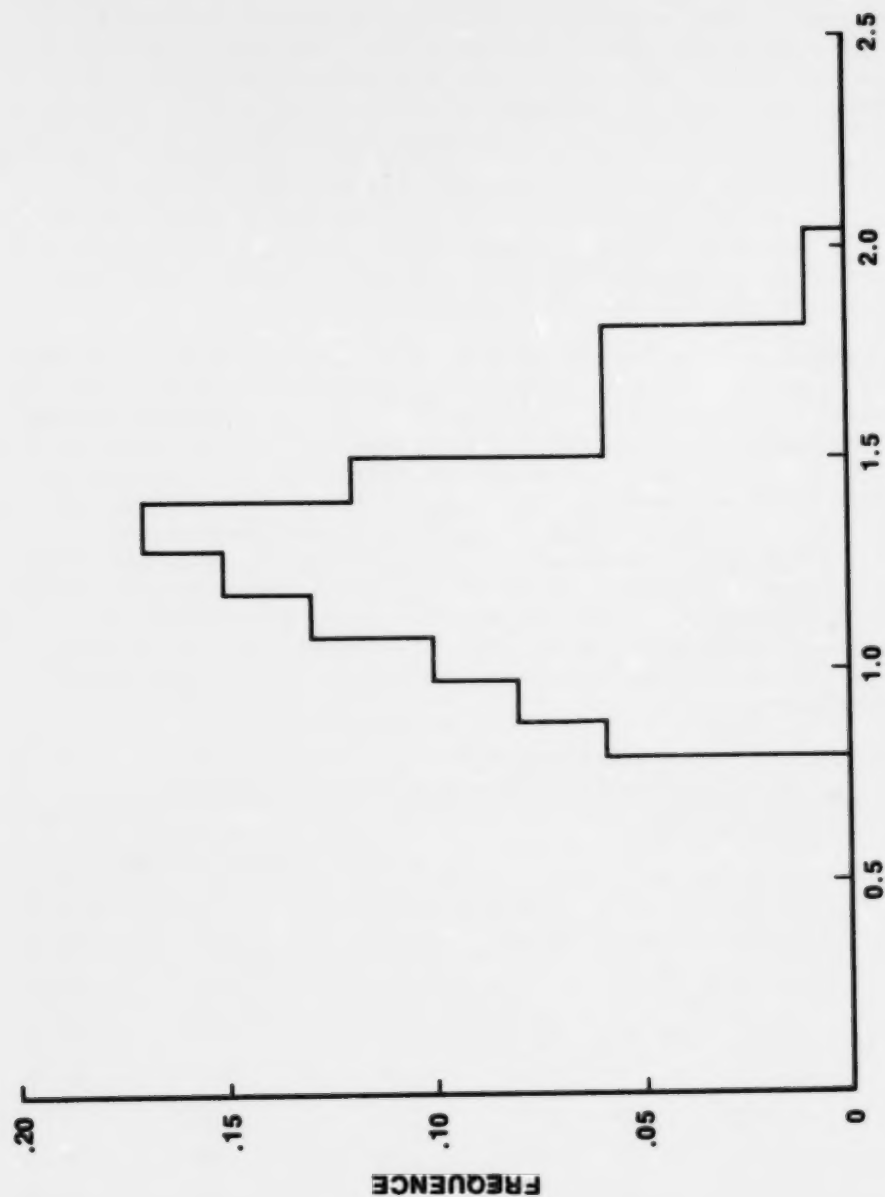


FIGURE 9. Statistical distribution of timing errors (number of days departure from recommended Irrigation Date) Under Imperfect Scheduling Regime.



RATIO OF SIMULATED IRRIGATION TO RECOMMENDED IRRIGATION

FIGURE 10. Statistical distribution of errors in quantity of water applied under the imperfect irrigation scheduling regime; (expressed as a ratio of actual to recommended quantities).

It was found that crop type and the quantity of water applied were closely correlated with runoff. Rate of application was of equal importance with quantity applied; i.e., either of these factors was suitable for use in the regression. Antecedent moisture conditions also appeared to affect runoff to a minor extent. Slope, length of run and time, were found to be unusable as predictors. That is not to say that they are unimportant, but in the stepwise regression they produced results that were either unreasonable or insignificant. Upon examination of the plots and the histograms it was found that the statistical distributions of the slope and length of run may have been too uneven to permit their use in a regression model. For example, the regression procedure assigned a negative coefficient to slope, indicating runoff would decrease with increasing slope (Figures 11 and 12). From the histogram in Figure 11, it is seen that a disproportionate number of fields had low slopes. Because of the inherent fluctuations in runoff, a large sample set will have a greater range of scatter than a small sample. Probably because of this, the highest runoff values at the lowest slope were greater than those at the highest slope, as indicated by Figure 12. This would explain the negative regression coefficient.

A linear regression equation was recalculated for each crop using water applied and total available storage capacity in the root zone (Table 4). As indicated by the R^2 values, the predictive ability of these regression equations was low. Consequently, they could not be expected to reproduce the wide range of observed runoff events. For these reasons it was decided that a statistical runoff model was needed. Such a model would not recreate the runoff from any single irrigation, but it could recreate the statistical distribution of a large number of events. A high degree of variability in runoff might be expected to produce different average sediment and TDS loads in return flows than would result from a narrower range of variability. Because the simulated runoff were to be used to estimate TDS and sediment loads in return flows it was important that the variability of the runoff be accurately simulated.

TABLE 4. RUNOFF MODEL COEFFICIENTS AND CORRELATION
COEFFICIENTS RESULTING FROM LINEAR REGRESSION

Crop	a_0	a_1	a_2	a_3	Number of Observations	R^2
Alfalfa	-2.781	0.202	0.140	1.0	88	0.39
Beans	0.129	0.125	0.011	1.0	313	0.20
Peas	0.335	0.121	0	1.5	157	0.15
Potatoes	-0.494	0.194	0.027	1.5	143	0.46
Sugar Beets	-0.236	0.131	0.131	1.0	123	0.39
Barley	-0.322	0.234	0.012	2.0	58	0.41
Spring Wheat	-0.440	0.206	0.025	2.0	55	0.31
Winter Wheat	-0.023	0.087	0.006	1.0	49	0.36
Wheat and Barley	0.081	0.090	0.013	2.0	41	0.32

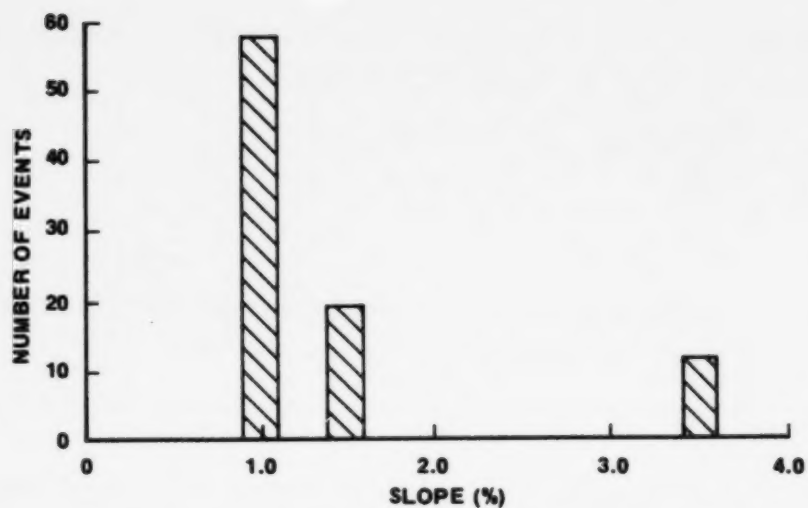


FIGURE 11. Histogram of 88 irrigation events on alfalfa with various field slopes.

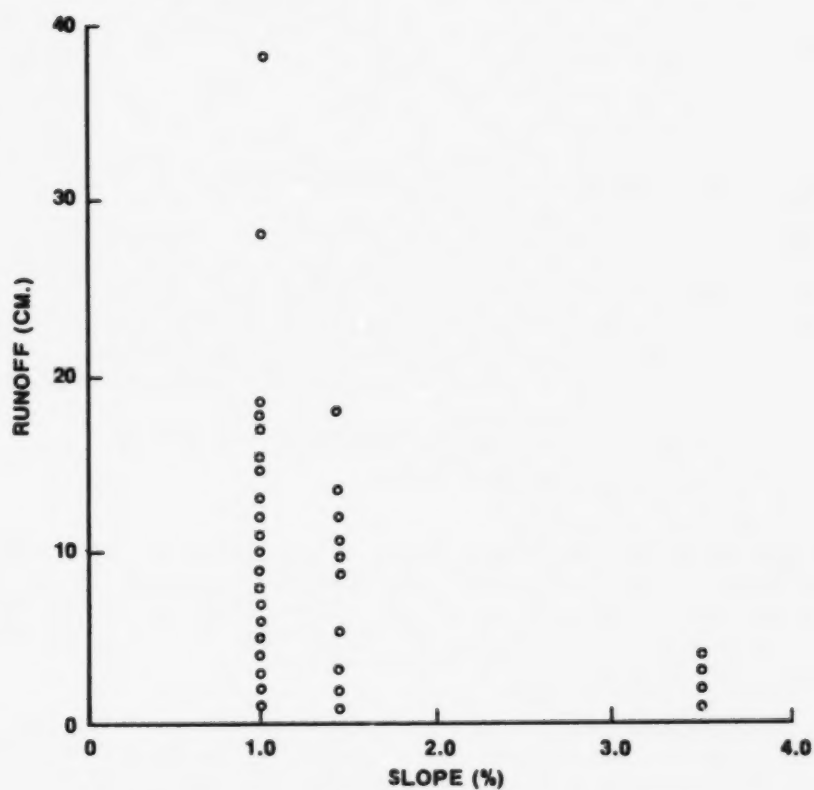


FIGURE 12. Surface runoff for 88 irrigation events on alfalfa with various field slopes.

Normalized errors were calculated for each irrigation event by the equation:

$$E_i = \frac{R_{a_i} - R_{D_i}}{R_{D_i}} \quad (13)$$

in which

- E_i = normalized error in runoff prediction for the i th event,
- R_{a_i} = actual runoff from i th irrigation event,
- R_{D_i} = runoff predicted by the regression model for the i th event.

For each crop the statistical distributions of these normalized errors were determined. In simulating irrigation events these distributions were used to generate random deviations from the runoffs predicted by the regression equations. That is, for each simulated irrigation the runoff was estimated by:

$$R_j = R_{D_j} \cdot (1 + E_j) \quad (14)$$

where

- R_j = simulated runoff for the j th event,
- $R_{D_j} = \alpha + B_1 S_j + B_2 (Q - Q_0) + E_j$
- α, B_1, B_2 = regression coefficients,
- S_j = antecedent available capacity in the root zone at the time of the j th simulated irrigation event,
- Q_j = quantity of water diverted for the j th simulated irrigation event,
- Q_0 = minimum application for runoff to occur,
- E_j = the random error term.

The reason for using the normalized error to characterize the random component, rather than the absolute error, was that the magnitude of the error will depend upon the amount of water diverted. The normalized errors were found to be fairly evenly distributed over the full range of values of diversions, as illustrated for wheat fields by Figure 13.

Under a scheduling regime, the timing and amount of water applied will change. The change in timing implies a change in the antecedent moisture conditions. The model that was formulated accounts for these factors explicitly in the regression equation. All other determinants of runoff for each crop are assumed to be accounted for by the random component and

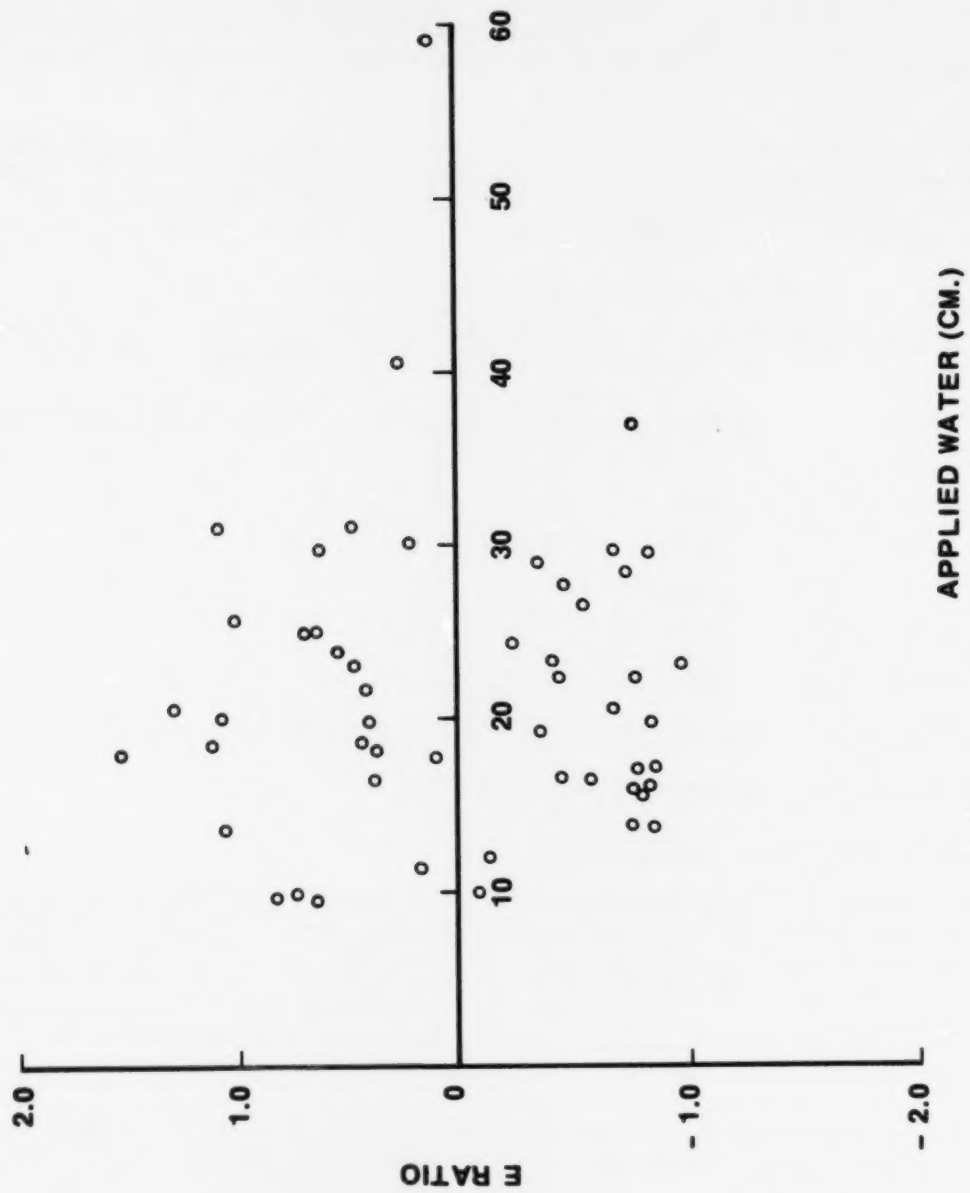


FIGURE 13. E ratio and the amount of water applied to wheat fields.

therefore, in this model, are implicitly assumed to be unaffected by scheduling. Obviously a model that combines a statistical component with a linear function of just water applied and antecedent moisture conditions cannot be considered a reliable predictive model for field use. Nevertheless, the investigators feel that it is adequate for estimating the regional change in runoff that would ensue from the use of a scheduling service. The large number of irrigations used to calibrate the model (1050) should insure that the statistical characteristics of the runoff will also be reproduced by the model.

To test the predictive ability of the runoff model, the original set of 1050 runoff events were estimated. The mean and standard deviations of the estimated runoff events for all crops were reasonably close to the actual events (Table 5). The errors indicated in Table 5 were judged to be

TABLE 5. STATISTICAL CHARACTERISTICS OF ACTUAL AND ESTIMATED RUNOFF DATA

Crop	Actual Runoff Data (cm)		Estimated Runoff Data (cm)	
	Mean	Std. Deviation	Mean	Std. Deviation
Alfalfa, pasture	6.4	6.0	6.5	7.4
Small Grains	2.9	2.4	3.0	2.3
Beans	2.3	1.7	2.2	1.6
Peas	3.0	2.4	2.7	1.9
Potatoes	2.6	2.2	2.8	2.2
Sugar Beets	3.3	2.5	3.2	2.2
All Crops	3.1	1.20	3.0	3.3

acceptable for the purposes of this analysis.

Spatial Variability of Applications

One other important assumption which was made in the irrigation model was that applied water was distributed uniformly over the fields. However, since furrow irrigation was the predominant method it must be recognized that, in fact, infiltration of water would be rather variable and this could cause errors in estimates of percolation. To evaluate the significance of the assumption of uniform applications, a test case was analyzed. The characteristics of the test were the following:

- (a) A 3-foot (91.4 cm) root zone was assumed, roughly the same as the root zone used for most crops in the study.
- (b) The soil moisture prior to irrigation was set at each of five different levels; 20 percent (by volume), 22.5 percent, 25 percent, 26 percent, 27.5 percent.

- (c) Two example irrigations were run, one in which it took 8 hours for the stream to reach the end of the furrow and one in which it took 12 hours. (All study fields had slopes of 1.0 percent or more). Set time was assumed to be 24 hours.
- (d) Since consumptive use rates affect total percolation, two rates were considered: one at mid-season (high rate) and one at end of season (low rate).

Twenty combinations were therefore considered. For each combination the drainage following an irrigation was computed in two ways. First, the field was divided into four segments representing the first 36 percent of the run, the next 28 percent of the run, the next 21 percent of the run, and the last 15 percent of the run (these were assumed arbitrarily to be the distances traveled by the stream in the first, second, third and fourth quarters of the total advance time). Water intake for each segment was determined from a cumulative infiltration curve prepared by USBR from studies in these fields. A typical curve was used (USBR, 1971, pages 90-92). The resulting soil moisture level for each segment was determined and total drainage, from time of irrigation until cessation of gravity drainage, was calculated. The area-weighted average drainage was then computed for the entire length of run.

The second way was to compute total drainage without regard for spatial variability, as was done in the model. Drainage estimates by these two methods were compared (Table 6). In summary, the assumption of uniform distribution resulted in overall estimates of percolation that were 1.3 percent low for the 8-hour case and 5.5 percent low for the 12-hour case. These figures represent average of errors weighted by volume of percolation. Large percentage errors occurred in a few cases, but were associated with small total percolation, hence their significance was negligible. For the 1.0 to 2.0 percent slopes common in the study area the 8-hour case is considered typical. It therefore seems likely that the order of magnitude of error should be well below 5 percent.

Distribution System Losses

Distribution system losses simulated by the irrigation model included percolation from head ditches and non-beneficial consumptive use. Losses measured by the USBR were used to develop a simple linear relationship between distribution losses and the amount of water diverted. Non-beneficial consumptive use was estimated as a linear function of evapotranspiration rates using a simple formula calibrated by the USBR for each farm during each year of the 1964-68 water use study (USBR, 1971).

SALINITY MODEL

The salinity model predicts TDS concentrations in water percolating beyond the root zone on the basis of the chemical composition of applied water and seasonal leaching fraction. Estimated total salt load in deep percolation is then calculated as the product of estimated TDS concentration and

TABLE 6. VARIABILITY OF PERCOLATION IN FURROWS

Time to end of furrow	ET Rate	Initial Soil Moisture	Drainage in Centimeters For Each Segment				Segment Overall	
			36%	28%	21%	15%	Field Weighted Average	Field Average % Error
8 hours	High	20%	0	0	0	0	0	0
8 hours	High	22.5%	.91	.74	.46	.05	.64	.74 12.3%
8 hours	High	25%	2.41	1.91	1.63	1.04	1.91	1.91 -0.3
8 hours	High	26%	3.73	3.05	2.31	1.68	2.95	3.05 -3.8
8 hours	High	27.5%	5.10	4.55	4.09	3.3	4.47	4.47 0
8 hours	Low	20%	0	0	0	0	0	0
8 hours	Low	22.5%	.46	.20	.01	0	.25	.20 +21%
8 hours	Low	25%	1.30	1.02	.79	.46	.99	1.02 -2.5
8 hours	Low	26%	2.15	1.68	1.27	.84	1.64	1.68 -2.4
8 hours	Low	27.5%	3.53	2.98	2.52	1.78	2.90	2.90 0
12 hours	High	20%	0	0	0	0	0	0
12 hours	High	22.5%	.23	.13	0	0	.12	.08 -34.8%
12 hours	High	25%	1.14	.84	.36	.15	.74	.69 -7.8%
12 hours	High	26%	1.88	1.32	.69	.41	1.16	1.09 -1.4
12 hours	High	27.5%	3.25	2.61	1.42	.91	2.34	2.25 -3.9
12 hours	Low	20%	0	0	0	0	0	0
12 hours	Low	22.5%	.74	.51	0	0	.41	.28 -31.3
12 hours	Low	25%	2.11	1.68	.94	.61	1.52	1.40 -7.9
12 hours	Low	26%	3.45	2.41	1.40	.99	2.36	2.03 -14.4
12 hours	Low	27.5%	4.83	4.19	2.54	1.80	3.71	3.82 +2.9

estimated volume of deep percolation.

The salinity model used in this study was developed at the U.S. Salinity Lab (Rhoades, et al., 1974). That model predicts specific ion concentrations in the leachate based upon chemistry of applied water, leaching fraction and soil characteristics.

The chemistry of irrigation water used in the A and B District was found to be fairly constant. However, in some seasons during the five years of the USBR study, there was an appreciable amount of rainfall. It was assumed that rainfall occurring during the growing season would dilute the total applied water proportionately. That dilution was as much as 30 percent in some cases. The salinity lab model was therefore used to estimate salinity of leachate at four different levels of dilution of applied water, 0, 10 percent, 20 percent and 30 percent.

Four curves were derived by regression on discrete data points generated by the model (Figure 14). Each curve represents one of the four levels of dilution. These regression models were incorporated into the case study and seasonal leaching fraction was computed for each field. Total rainfall and applied water were used to determine the level of dilution of applied water. The TDS concentrations associated with the calculated leaching fraction were calculated for each field by interpolating between the appropriate curves.

Salinity of surface runoff was assumed to be the same as that of applied water, since USBR field data showed no appreciable difference between the two.

The salinity model was not locally calibrated and could not be expected to precisely predict salt loading from any single field in any one year, since significant data errors are inevitable and the model bias is not known. Nevertheless, for purposes of predicting changes in regional average salt loading, the model is considered adequate because random errors will tend to cancel out and model biases will be mitigated by virtue of the fact that the analysis is concerned with differences in model predictions under differing irrigation regimes.

In the case of the A and B District, reductions in regional TDS loads in return flows would be accompanied by a decrease in calcium concentrations relative to sodium, which would increase sodium adsorption ratios of return flows. At the same time, alkalinity would be reduced.

SEDIMENT MODEL

Sediment loading was regarded as an indicator of nitrogen, phosphorous and pesticide concentrations in return flows, since these factors are directly linked to erosion rates (Carter and Bondurant, 1976). The sediment model predicts sediment concentrations in surface runoff on the basis of the rank*

*The rank of an irrigation refers to its order in a sequence of irrigations in one particular field, e.g., the first, second, third, etc.

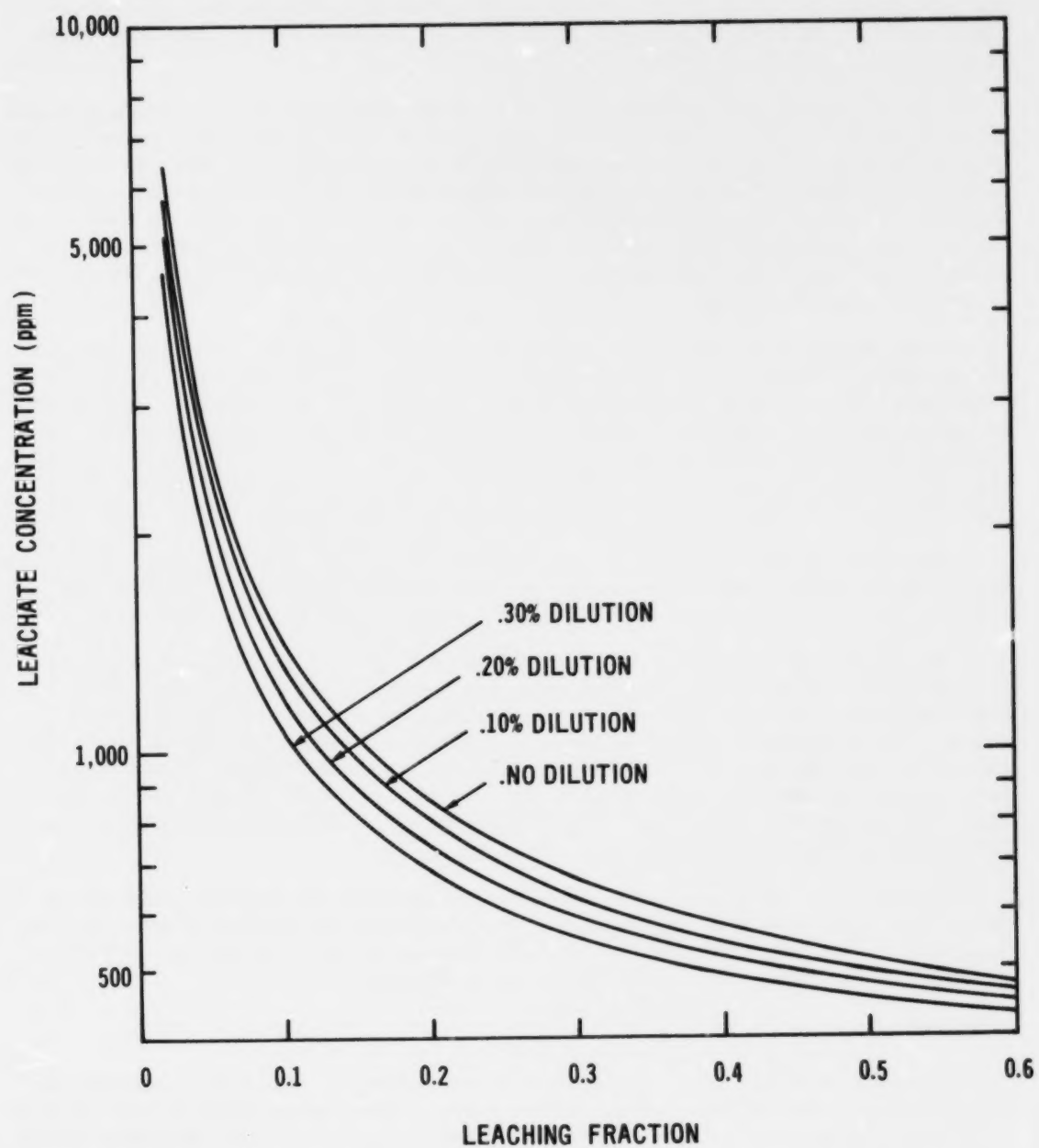


FIGURE 14. Salinity concentration of leachate for four irrigation water dilution levels by leaching fraction. (Source: Rhoades et al., 1974)

of each irrigation event and the volume of water applied per unit of land area. Sediment loads in surface runoff are extremely variable and difficult to predict. Nevertheless it was possible to estimate sediment loads in the case study using a simple model calibrated with USBR measurements of sediment concentrations in surface runoff. Although it cannot be claimed to be an accurate predictor of sediment loads in return flows from any single irrigation event, the model can be expected to produce a reasonably accurate estimate of aggregate sediment loads from the A and B District under different scheduling regimes.*

The rate of sediment loss from a furrow irrigated field can be expected to be initially high at the beginning of an irrigation, then decline rapidly during the irrigation until it approaches a steady state (Figure 15). Total sediment loss for an irrigation will generally be higher with the first irrigation of the season and decline with subsequent irrigations (Hagan, et al., 1967, p. 957). However, cultivation of fields can cause high total sediment losses later in the season (Busch, et al., 1975).

Sediment data collected in the A and B District by the USBR were used for development of the model. The data consisted of grab samples of runoff from each of the fields at various times during the season. A single sample was taken for each irrigation; that is, there were no multiple samples from any single irrigation. With this data limitation in mind the model was formulated on the basis of the following postulates:

- (1) Each sample must be considered a single random sample from a statistical distribution of sediment concentrations that would look similar to the curve shown in Figure 15. The statistical distribution coincides with the distribution of concentrations with time.
- (2) The shape of the curve typified by Figure 15 will change with each irrigation, as ground surface conditions and crop development proceed. In general it may be supposed that there is a representative curve for first irrigations, another representative curve for second irrigations, etc.
- (3) The time integral of these representative curves can be estimated, as an approximation, from the average concentration of all those samples taken during first irrigations, all those taken during second irrigations, and so on.

*Note that it was assumed that only irrigation schedules would change. The changes in irrigation techniques that might result in conjunction with irrigation scheduling were not considered.

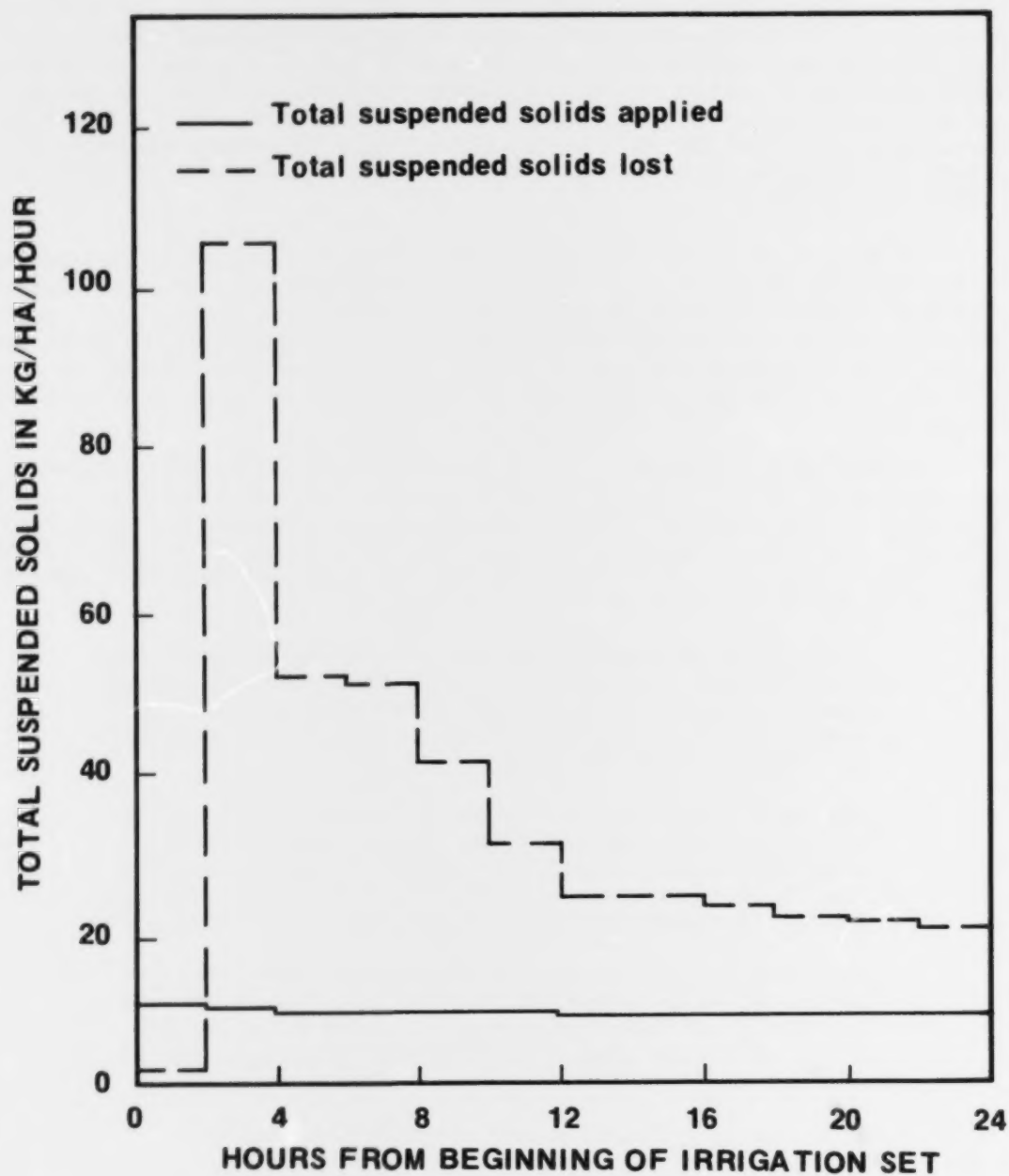


FIGURE 15. Total suspended solids gained and lost during an irrigation set (after Busch, *et al.* 1972).

- (4) Forage crops are generally not tilled and have essentially full cover early in the season so it may be assumed that sediment losses from such crops are constant and relatively low during the season.
- (5) The average total sediment load from an irrigation will be the product of the average concentration and the total volume of runoff.

The fifth postulate would be true if the rate of runoff were constant during an irrigation. This will not actually be the case, however. Runoff rate will increase very rapidly at first and then continue to increase slightly during the remainder of the time water is applied, as illustrated by Figure 16. This has the affect of causing the product of the average concentration and the volume of runoff to slightly overestimate total sediment loads in runoff.* Since field data on the time distribution of surface runoff for each individual field were unavailable, a constant correction factor was applied to the average estimated by the method described above. The correction factor was determined by analysis of the hydraulics of flow in typical fields in the area. The factor used was 0.75.

USBR field data on average sediment concentrations were assembled and the ranking of each irrigation was determined. The average concentration for each rank was then determined (Table 7). From these averages, the following regression model was derived:

$$S_a = 1832 R^{-0.3374} \quad (15)$$

in which

S_a = average sediment concentration, in mg/l,
 R = rank of irrigation

This regression function is displayed in Figure 17.

The 0.75 correction factor was determined by first developing typical curves for the time distribution of concentrations and the time distribution of runoff. The data from all rank 2 irrigations were used to estimate the distribution of concentrations. The distribution of runoff rates was estimated by selecting typical field characteristics and using a typical application rate, time of set and furrow intake rates for the A and B District. The typical values chosen were based on data reported by the USBR (1971).

*As an example, the sediment load for the case illustrated in Figures 15 and 16 would be overestimated by 26 percent by the method indicated in steps 1 through 5.

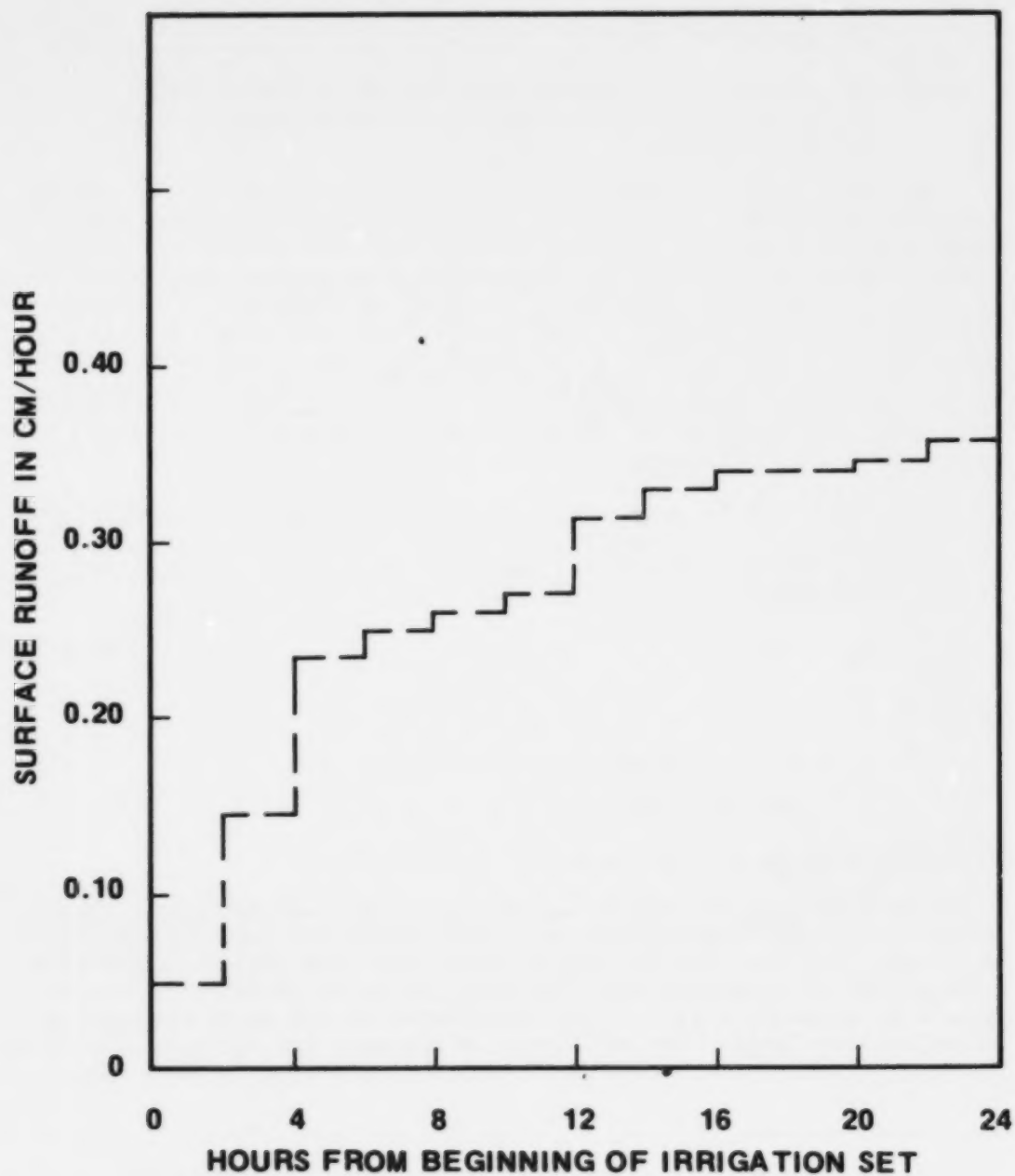


FIGURE 16. Rate of runoff from a furrow irrigated field (after Busch et al. 1972).

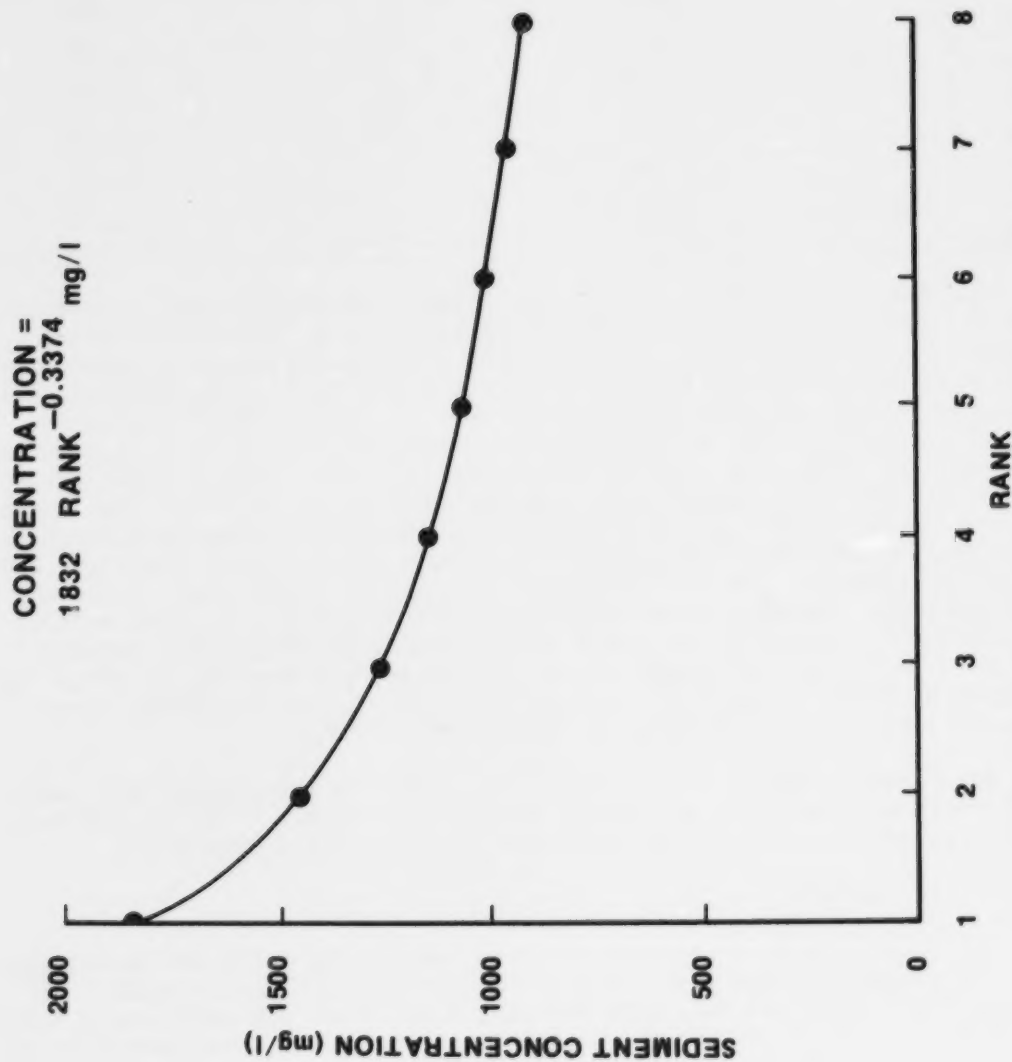


FIGURE 17. Relationship of sediment concentration to rank of irrigation event for non-forage crops in the A and B District.

TABLE 7. SEDIMENT CONCENTRATIONS IN RUNOFF FROM
NON-FORAGE CROPS BY RANK OF IRRIGATION

Rank of Irrigation	Average Sediment Concentration (mg/l)	Number of Irrigations Sampled	Average Sediment Load Estimated by Regression (mg/l)
1	1,847	34	1,832
2	1,611	26	1,450
3	1,134	24	1,264
4	1,049	14	1,147
5	796	11	1,064
6 and above	1,243	15	1,008

The model thus derived, while very simple, can be expected to predict regional average sediment loads fairly well. To more accurately predict sediment loads of individual irrigations it would be necessary to examine many additional relevant factors, such as furrow shape, rate of application, soil roughness, slope, stage of crop growth, etc. Initially, these and other factors were considered in the analysis. An attempt was made to incorporate them into the model, but with no notable success. The simpler model presented above is adequate for examining the question of interest: what would be the A and B District sediment load under the 1975 existing irrigation practice, and what would the regional load have been if total water use and irrigation frequency had been altered by irrigation scheduling? Since the sediment loads estimated by this model are based on local data and reflect the influence of quantity of runoff and frequency of irrigations (through rank of irrigations) the model will be adequate for estimation of the change in sediment loads in the A and B District as scheduling procedures change, i.e., as quantity and frequency of irrigations change.

For forage crops, a simpler model was used. It was assumed that sediment concentrations would not change during the season. Based on USBR data, an average concentration of 343 mg/l was estimated for forage crops.

CROP PRODUCTION MODEL

The crop production or yield model estimated crop yield per acre based on the information provided from the soil moisture and irrigation model. It is generally recognized that poor irrigation practices can reduce crop yields in several ways. If too little water is applied, overall crop growth is reduced and losses due to certain hazards such as weeds or frost may be increased. At certain critical times, fruit development may be greatly impaired or, if too much water is applied, yield reductions may result from poor soil aeration, excessive vegetative growth at the expense of fruit yield, or difficulties with harvesting due to lodging of grains.

The crop production model conceived for this project had three components. The first was a submodel for estimating the potential yield based upon seasonal evapotranspiration. The second was a linear regression model which predicted yield deficit that would be attributable to poor timing of applications or excessive water use. The third was a coefficient of adjustment intended to account for unexplained variations in yields. The overall model may therefore be represented by the following equation.

$$Y_A = Y_p \cdot (1 - D) \cdot C_u \quad (16)$$

in which

- Y_A = final estimate of yield,
- Y_p = potential yield based upon seasonal evapotranspiration,
- D = yield deficit, expressed as a decimal fraction of potential yield, which would be predicted on the basis of excessive water use or mistimed applications,
- C_u = a coefficient which adjusts for unexplained variations in yield.

Potential Yield Submodel

Potential yield (Y_p) was predicted based on a crop production model developed by Stewart, et al. (1973). Inherent in the model is the assumption that there exists a maximum attainable yield for any given cultural practices and circumstances of climate and soil (Y_M) and that there exists some maximum beneficial evapotranspiration (ET_M) associated with Y_M . The ratio of predicted to maximum yield, $\left(\frac{Y_A}{Y_M}\right)$, is considered to be a linear function of the ratio of actual ET to the yield maximizing evapotranspiration $\left(\frac{ET_A}{ET_M}\right)$. In Figure 18, O' represents the upper limit of the function. At O' the maximum yield is achieved (100% of Y_M) when the maximum beneficial ET (100% of ET_M) is reached. If the actual season total evapotranspiration (ET_A) is less than ET_M the yield will fall below 100 percent of Y_M . In that case the relationship between the ratio $\left(\frac{Y_A}{Y_M}\right)$ and the ratio $\left(\frac{ET_A}{ET_M}\right)$ is represented by a straight line through O' having a slope β_o .

The coefficient β_o is defined by the equation,

$$\beta_o = \frac{-(\% \text{ reduction in yield below } Y_M)}{-(\% \text{ reduction in ET below } ET_M)} \quad (17)$$

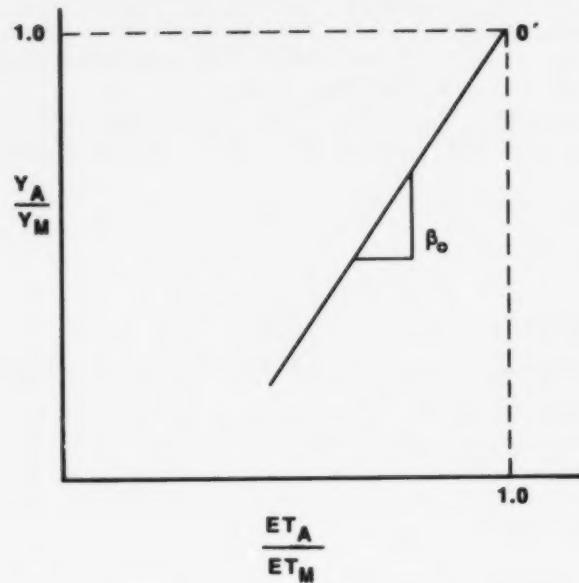


FIGURE 18. General nature of the crop production function of Stewart and Hagan (1969).

β_0 is therefore referred to as the yield reduction ratio. Values of β_0 have been derived experimentally by Stewart and Hagan (1969) for several crops. When not available from field experiments, the value of β_0 may be estimated from other water use-yield data, under some circumstances.

The algorithm for estimating potential yield is therefore defined by the equation:

$$\left(\frac{Y_A}{Y_M}\right) = 1 - \beta_0 \left(1 - \frac{ET_A}{ET_M}\right) \quad (18)$$

For each crop in the case study it was therefore necessary to determine the maximum expected yield (Y_M), the associated yield-maximizing ET (ET_M) and the coefficient β_0 , for use in these equations.

Initially, plots of yield vs. ET for each crop in the 204 historical cases were made. From these plots a maximum yield and associated maximum ET were selected. Y_M was not necessarily the highest yield recorded in the historical cases. Rather, it was selected to represent a "good" yield

relative to the majority of recorded yields. The slopes of the yield functions, represented by the β_0 coefficients, were determined from several sources.

The value of β_0 used for beans was the average of coefficients determined experimentally by Stewart, et al. (1973, 1976) for three varieties. It was assumed that water use and ET are equivalent when water use is very low and the water is carefully applied. The β_0 value for sugar beets was derived from field data presented by Larsen and Johnston (1955) in which these conditions were met. The β_0 value for wheat was based on a yield-water use model developed from experimental data by Whittlesey and Colyar (1968) in which, again, these conditions were met. The coefficient for barley was assumed to be the same as that for wheat, and the coefficient for peas was assumed the same as that for beans. These assumptions, while essentially arbitrary, were based upon a subjective evaluation of data presented for a wide range of crops by Downey (1972). The models, derived as described above, were rewritten as linear equations for yield as a function of seasonal ET as follows.

<u>Crop</u>	<u>Potential Yield (English Units)</u>
Spring Wheat	$7.59 \cdot ET - 27.23$ (bu./ac.)
Winter Wheat	$9.38 \cdot ET - 37.5$ (bu/ac.)
Barley and Mixed Grains	$8.46 \cdot ET - 25.38$ (bu/ac.)
Potatoes	$42.86 \cdot ET - 514.3$ (cwt/ac.)
Sugar Beets	$1.5 \cdot ET - 12.0$ (tons/ac.)
Beans	$5.0 \cdot ET - 45.0$ (cwt/ac.)
Peas	$3.54 \cdot ET - 3.54$ (cwt/ac.)

Alfalfa yields were predicted by a simpler model. Stewart and Hagan (1969) have presented data illustrating a clear linear relationship between alfalfa yields and ET. Therefore alfalfa yield predictions for this study were made by simply multiplying historical yields from each field by the ratio of predicted ET to historical ET.

Stewart and Hagan (1969) have stated that the general model described above can be used to predict crop yields under a wide range of circumstances. However, a few cautionary comments are in order. First, a crop grown under very adverse conditions may experience tissue damage, even while satisfying evapotranspiration demands. The crop may then respond differently to evapotranspiration than would be the case under normal growing conditions. The coefficient β_0 is only intended to be used under normal growing conditions. Secondly, β_0 may have a unique value for each variety of a crop. Finally, Equation 18 is only valid if crop stresses are distributed evenly throughout

the season. If severely unbalanced stresses occur, yield will fall below the potential yield indicated by the straight line emanating from 0' in Figure 18. Where such unbalanced stresses occur, Stewart and Hagan have proposed a model in which β_0 is determined by the relative degree of stress at each of three growth periods during the season.

Yield Deficit Submodel

The model described above predicts yield as a function of moisture stress. Yield deficits may be caused by a host of other factors. The state of the art of crop production modeling has not yet advanced to the point where complete models formulated from first principles can account for all such factors. Therefore a purely empirical regression model was developed for the present study which might explain some departures from predicted yields. The general procedure was as follows:

- a) Recorded crop yields for each field were adjusted to account for losses due to hazards specifically noted by the USBR and unrelated to water use (e.g., losses due to frost or hail). (Where such hazard losses were noted by the USBR an estimate of the percentage of loss was made and published with the USBR data set.) The adjusted yield was therefore:

$$\text{Adjusted yield} = \frac{\text{Measured yield}}{1 - \left(\frac{\text{Estimated \% Loss}}{100} \right)} \quad (19)$$

This adjusted yield therefore represents an estimate of the yield that would have been realized in the absence of the hazards noted.

- b) Using the Stewart-Hagan model for potential yield described earlier, an estimated potential yield was calculated for each field. The difference between the adjusted yield and the estimated potential yield was then regarded as a yield deficit for each of the 204 fields.
- c) A value for eight different indices of water use and soil moisture conditions (Table 8) were computed for the season as a whole, and for specific growth stages during the season, for each field. As an example, ET deficits for the vegetative, pollination and maturation stages of growing season, and for the whole season, were computed.
- d) A stepwise regression procedure was employed for each crop to select appropriate variables from among the indices described in (c).

TABLE 8. YIELD INDICES USED IN STEPWISE REGRESSION
ANALYSIS FOR YIELD DEFICITS

Variable		Variable Description
No.	Name	
(1)	ETDEF	ET Deficit (attainable ET minus actual ET)
(2)	MSMT	Average soil moisture tension
(3)	MSMP	Average soil moisture percentage
(4)	IRR	Quantity of water applied
(5)	ARET	Integral of the quantity (% soil moisture - 30.7) for those days when soil moisture was higher than the limit of gravity drainage (30.7% by volume).
(6)	ADEPT	Integral of the quantity (CRIT - soil moisture tension) for those days when soil moisture was lower than 50% available soil moisture, where CRIT represents tension at 50% available soil moisture.
(7)	ERAIN	Net rainfall
(8)	NIRR	Number of irrigations

The variables, coefficients and correlation coefficients used in the stepwise regression models for yield deficits for each crop are shown in Table 9. Note that a positive coefficient indicates a positive contribution to yield deficit, and a negative coefficient indicates a "negative" contribution to deficit.

A third component (C_u) was included in the crop production model to account for unexplainable yield variations. It was assumed that this component would be constant for any given field under all of the three irrigation regimes. Thus if C_u was observed to have a certain value for a given field under the unscheduled regime it was assumed that the same yield adjustment would be necessary for yield predictions associated with the scheduled regimes. That is, if

Y_o = the recorded yield for a given field,

and

Y_{p_u} = predicted yield under the unscheduled regime,

Then
$$C_u = \frac{Y_o}{Y_{p_u}} \quad (20)$$

TABLE 9. YIELD DEFICIT REGRESSION MODELS

Crop	Equation	Correlation Coefficient (R)
Beans (cwt/ac.)	$Y_D = 113.538 - 64.269 \text{ MSMT } (0) + 0.4839 \text{ ADEPT } (10) - 6.345 \text{ ETDEF } (1)* - 2.5788 \text{ MSMP } (0)$	0.79
Barley and Mixed (bu/ac.)	$Y_D = 29.77283 + 10.6246 \text{ ETDEF } (0) - 22.533 \text{ MSMT } (0) + 0.70193 \text{ IRR } (0)$	0.62
Peas (cwt/ac.)	$Y_D = 26.995 - 3.88426 \text{ ERAIN } (0) - 0.2033 \text{ ARET } (0) + 0.50025 \text{ IRR } (0)$	0.67
Potatoes (cwt/ac.)	$Y_D = 229.657 - 6.74792 \text{ MSMP } (1)* + 0.73037 \text{ ADEP } (3)*$	0.71
Wheat (bu/ac.)	$Y_D = 12.288 + 10.0982 \text{ NIRR } (0) + 9.3249 \text{ ETDEF } (0)$	0.77
Sugar Beets (tons/ac.)	$Y_D = 52.6843 + 0.08352 \text{ ARET } (0) - 2.22109 \text{ MSMP } (0) - 2.26122 \text{ ETDEF } (0)$	0.83
Winter Wheat (bu/ac.)	$Y_D = -43.765 + 26.741 \text{ NIRR } (2)* + 28.758 \text{ NIRR } (1)*$	0.84

*Note: a variable name followed by a subscript in parentheses represents the value of the variable calculated for a particular period; 0 = full season, 1 = vegetative period, 2 = pollination/fruit set, 3 = maturation.

The various periods established for each of the crops are summarized below:

Period 1 for beans: planting to full cover minus 15 days
 Period 1 for potatoes: planting to 20 days after emergence
 Period 3 for potatoes: full cover to harvest
 Period 1 for winter wheat: planting to full cover minus 15 days
 Period 2 for winter wheat: full cover minus 15 days to full cover plus 15 days

The value of C_u thus determined was then used for estimating yields for that field under any irrigation regime. Thus in effect, the models were calibrated separately for each field.

Given the state of the art of crop production modeling it is not possible to have a great deal of confidence in the predictions made by these models. In the particular circumstances of this study the inaccuracies are

probably greater still because the original yield data were evidently lumped for each farm. That is, if wheat were grown in two different fields of a farm the yields recorded were the average of the two, even though in many cases the fields were irrigated quite differently and perhaps planted at different dates and fertilized at different rates. Nevertheless, by including C_u it is felt that model biases would be largely nullified and predictions should have a degree of accuracy suitable for purposes of this study.

PHYSICAL ANALYTICAL SYSTEM RESULTS

The initial analysis of 204 fields produced interesting insights into the impacts which irrigation scheduling can have on water and return flows and it also put the historical irrigation practices of the study area into better perspective. It should be borne in mind, when viewing the initial results, that farmers in the A and B District are regarded as efficient in their use of water. Average annual diversions per irrigated acre are substantially lower in this district than in neighboring districts. However, the potential for beneficial changes in water use in this district is still great.

Water Use and Return Flows

Diversions and disposition of water, as well as average soil moisture levels were estimated for the 204 cases of the six-farm study for the unscheduled and scheduled irrigation regimes (Table 10). A significant increase in water use efficiency was estimated with the use of irrigation scheduling. Total diversions decreased by an estimated 24 percent for the ideal scheduling case and 8 percent for the imperfect scheduling case. The largest part of the water savings was due to reduced deep percolation. Delivery system losses and surface runoff decreased in rough proportion to the total diversions. A small reduction in surface runoff and a reduction in the amount of water left in the root zone after harvest accounted for the remaining change in diversions. The most dramatic changes were in deep percolation which was reduced by 78 percent under the ideal regime and 17 percent under the imperfect regime. Overall, if efficiency is defined as the ratio of evapotranspiration to total diversions, the estimated efficiencies under the unscheduled, ideal scheduled and imperfect scheduled regimes were 56 percent, 76 percent, and 60 percent, respectively.

Evapotranspiration increased slightly under ideal scheduling and decreased slightly under imperfect scheduling. While this seems anomalous it is in fact quite reasonable. Under ideal scheduling no serious soil moisture deficits occurred whereas under imperfect scheduling such deficits did occur from time to time. When such a deficit occurred the soil moisture model reduced evapotranspiration to compensate for low soil moisture. Also, under imperfect scheduling, soil moisture deficits were occasionally followed by an irrigation application which was not sufficient to fill the soil profile. Thus the crop would not attain the full potential evapotranspiration rate even after the irrigation, and cumulative ET would fall behind that calculated for the ideal regime. On the other hand, farmers operating

TABLE 10. COMPARISON OF WATER USE FOR SCHEDULED AND UNSCHEDULED REGIMES IN 204 FIELDS

		Water Use (cm)		
		Unscheduled Cases	Scheduled Cases	
			Ideal	Imperfect
Diversions	(cm)	84.15	63.60	77.83
Transmission Losses and Phreatophytic Losses	(cm)	9.35	7.44	8.56
Rain	(cm)	7.47	7.47	7.47
Runoff	(cm)	14.43	11.28	13.26
Percolation	(cm)	20.19	4.47	16.76
Evapotranspiration	(cm)	7.24	48.03	46.81
Average Soil Moisture (% by Volume)	(cm)	25.82	26.55	25.77

without irrigation scheduling were generally applying more water than the imperfectly scheduled farms and also were irrigating more frequently. For that reason the unscheduled farmers rarely failed to completely refill the soil profile and therefore evapotranspiration almost always began at the full potential rate following each irrigation.

Average soil moisture is seen to be slightly higher for the ideal scheduled regime and slightly lower for the imperfectly scheduled regime than for the unscheduled regime. The reasons for this were the same as those mentioned above regarding evapotranspiration.

TDS concentrations in leachate were observed to increase under the scheduled regimes, as would be expected from the reduced leaching fractions anticipated under those regimes, but the total salt load was reduced because of the substantial reductions in total percolation (Table 11). Reductions in total sediment loads were due primarily to reduced frequencies of irrigation events. As discussed earlier, the irrigation events that would be eliminated under scheduled regimes would be the last ranked, i.e., those in which the sediment concentrations would be lowest. Thus the reduction in sediment loading is not proportionally as great as the reduction in irrigation frequency.

In addition to reducing total salinity and sediment loads in return flows, use of irrigation scheduling would affect various other water quality parameters. The general nature of these effects can be imputed from anticipated changes in salinity and sediment loads. In the case of the A and B District, reductions in regional TDS loads and return flow would have been accompanied by an increase in sodium concentrations relative to calcium, which would increase sodium adsorption ratios in return flows. At the same

TABLE 11. RETURN FLOW QUALITY, SCHEDULED AND
UNSCHEDULED REGIMES FOR 204 FIELDS

	Unscheduled	Ideal Schedule	Imperfect Schedule
Total TDS in Deep Percolation, kg/ha	1446	834	1350
Total Sediment Load in Surface Runoff, kg/ha	12935	8720	11141

time, alkalinity would have been increased. Chemical compositions of leachate in the A and B District are a function of leaching fraction (Table 12). These estimates were based upon the model developed by Rhoades, et al. (1974). To put Table 12 in proper perspective, regional average leaching fractions, as calculated from Table 9 would be 0.30 for the unscheduled regime and 0.09 for the ideal scheduled regime.

TABLE 12. ESTIMATED CONCENTRATIONS OF CONSTITUTENTS (meq/l) IN
LEACHATE AS A FUNCTION OF LEACHING FRACTION FOR
TYPICAL CIRCUMSTANCES* IN THE A AND B DISTRICT

Constituent	Leaching Fraction								
	.02	.04	.06	.08	.10	.20	.30	.40	.50
Ca	1.08	1.80	2.46	2.99	3.41	4.48	4.91	5.14	5.28
Mg	58.50	29.25	19.50	14.63	11.70	5.85	3.90	2.92	2.34
Na	38.50	19.25	12.83	9.62	7.70	3.85	2.57	1.92	1.54
K	4.50	2.25	1.50	1.12	0.90	0.45	0.30	0.22	0.18
Cl	23.50	11.75	7.83	5.88	4.70	2.35	1.57	1.18	0.94
CO ₃	3.54	1.18	0.76	0.61	0.55	0.46	0.44	0.43	0.42
HCO ₃	33.04	18.38	13.54	11.26	9.96	7.58	6.85	6.49	6.28
SO ₄	42.50	21.25	14.17	10.62	8.50	4.25	2.83	2.13	1.70
Alkalinity	36.58	19.55	14.30	11.87	10.51	8.03	7.28	6.92	6.70
SAR	7.05	4.89	3.87	3.24	2.80	1.69	1.22	0.96	0.79

*(a) Chemistry of applied water in meq/l: Ca = 2.34, Mg = 1.17, Na = 0.77, K = 0.09, CO₃ = 0.12, HCO₃ = 2.88, Cl = 0.47, SO₄ = 0.85

(b) Soil is calcareous; assume saturation with CaCO₃.

Sediment load may be regarded as an indicator of nitrogen, phosphorous and pesticide concentrations in return flows. Thus the substantial reductions in sediment load anticipated with irrigation scheduling would indicate that nutrients and toxic substances might also be reduced in return flows by significant amounts. The links between these factors and sediment concentrations have been clearly established by other research conducted in southern Idaho. Busch, et al. (1975) have shown that concentrations of nitrogen and phosphorous derivatives of fertilizers are clearly linked to concentrations of sediments in surface runoff. Carter and Bondurant (1976) concluded from a review of related literature that biocides in surface runoff are generally adsorbed on sediments, and that control of biocides in return flows can be accomplished by controlling sediment loads.

The environmental benefits discussed above were found to vary widely from one farmer to another and from one crop to another. This variability is illustrated by Table 13, in which the values of several parameters estimated for ten of the cases studied are summarized. Although the use of irrigation scheduling would have reduced the environmental impact of irrigation in most cases, it is interesting to note that in a few cases the reverse would have been true.

Imperfect scheduling resulted in fewer irrigation events than did ideal scheduling because a +35 percent bias in water applied under the imperfect regime resulted in higher post-irrigation soil moisture levels (Table 14). While much of that additional applied water was lost to deep percolation during subsequent days, nevertheless it also was used to some extent to satisfy evapotranspiration demand, thus postponing the next irrigation event for a day or two in many cases.

Seasonal patterns of water use and soil moisture in individual fields were often quite erratic. Four soil moisture histories were selected to illustrate this variation (Figures 19-20). These four histories illustrate some fairly typical patterns of irrigation timing by A and B District farmers. The pattern represented in field B, Figure 19, was commonly observed for several of the farms and crops. That is, the first irrigation was delayed until soil moisture was quite low, then succeeding irrigations were done at relatively high moisture levels. A tendency to allow alfalfa to mine water is fairly common with alfalfa because of the deep and well developed root system (Field A, Figure 20). Field A in Figure 19 and Field B in Figure 20 illustrate highly erratic irrigation schedules observed in many cases.

The models used in this analysis could be expected to predict regional values of the various quantities with sufficient accuracy. However, accurate estimates of specific values under any single set of circumstances are not within model capabilities. This raises a question about the validity of the estimated historical soil moisture plots presented in Figures 19 and 20. In the opinion of local experts, these plots do present a fair picture of local irrigation practices. In most of these cases the farmers applied considerably more water than was needed at each irrigation. Thus the soil moisture level was often reinitialized at the maximum holding capacity of the soil moisture. If the model were seriously biased, estimated soil

TABLE 13. RESULTS ESTIMATED FOR 10 CASES SELECTED FROM AMONG THE 204 CASES STUDIES:
EXAMPLES OF VARIABILITY OF RESULTS

Farm	1	2	3	4	5	6	7	8	9	10
Crops	Alfalfa	Alfalfa	Beans	Beans	Potatoes	Potatoes	Wheat	Wheat	Sugar Beets	Sugar Beets
Total Diversions (cm)*										
Unscheduled	62.2	225.6	39.1	104.9	211.3	145.5	71.1	49.8	165.1	123.4
Ideal Scheduled	98.3	98.8	60.5	53.8	66.3	57.7	48.3	37.8	74.7	89.7
Number of Irrigations										
Unscheduled	3	7	1	8	8	8	4	2	6	6
Ideal Scheduled	2	2	4	4	7	6	2	2	5	6
Total Runoff (cm)										
Unscheduled	11.2	77.0	11.9	37.3	39.4	23.4	10.7	4.8	20.8	21.1
Ideal Scheduled	22.9	22.9	6.9	9.9	9.9	6.9	3.6	4.6	13.5	18.5
Total Percolation (cm)										
Unscheduled	0	86.6	23.0	30.0	92.7	60.2	21.3	6.4	23.4	3.8
Ideal Scheduled	4.3	3.6	8.4	2.8	4.3	2.3	7.4	6.6	5.1	5.3
Total Leachate TDS (metric tons/ha)										
Unscheduled	0.0	3.542	0.941	1.547	3.788	2.533	1.255	0.650	1.412	0.65
Ideal Scheduled	0.897	0.829	0.740	0.628	0.628	0.538	0.717	0.583	0.762	0.672
Total Runoff Sediment (metric tons/ha)										
Unscheduled	0.269	2.51	1.61	3.40	3.85	2.51	1.18	0.589	1.85	1.93
Ideal Scheduled	0.555	0.555	.706	1.01	1.06	6.55	0.471	0.555	1.58	1.82

*Centimeters equivalent depth of application.

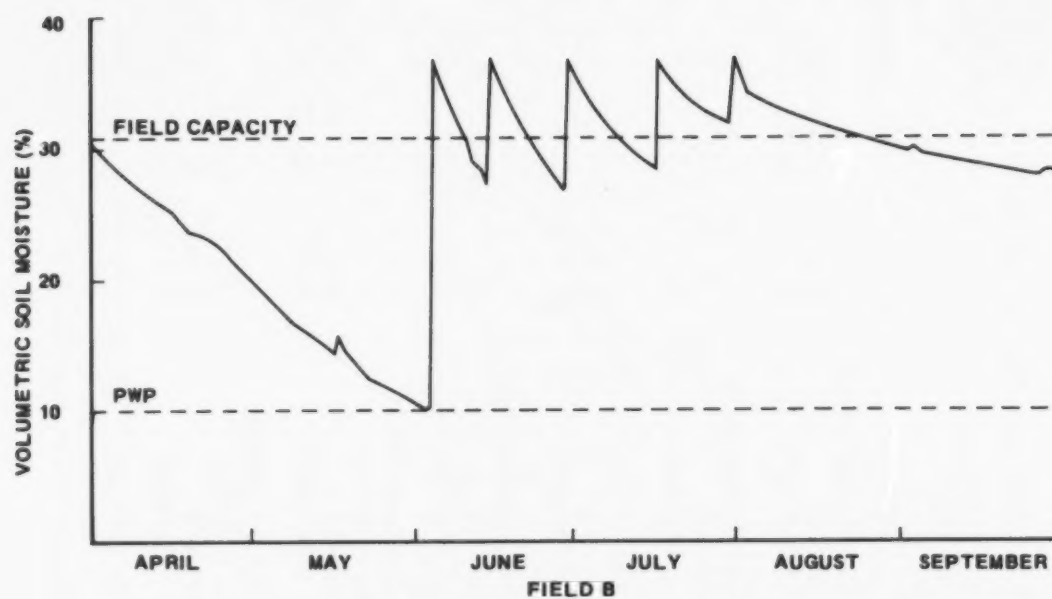
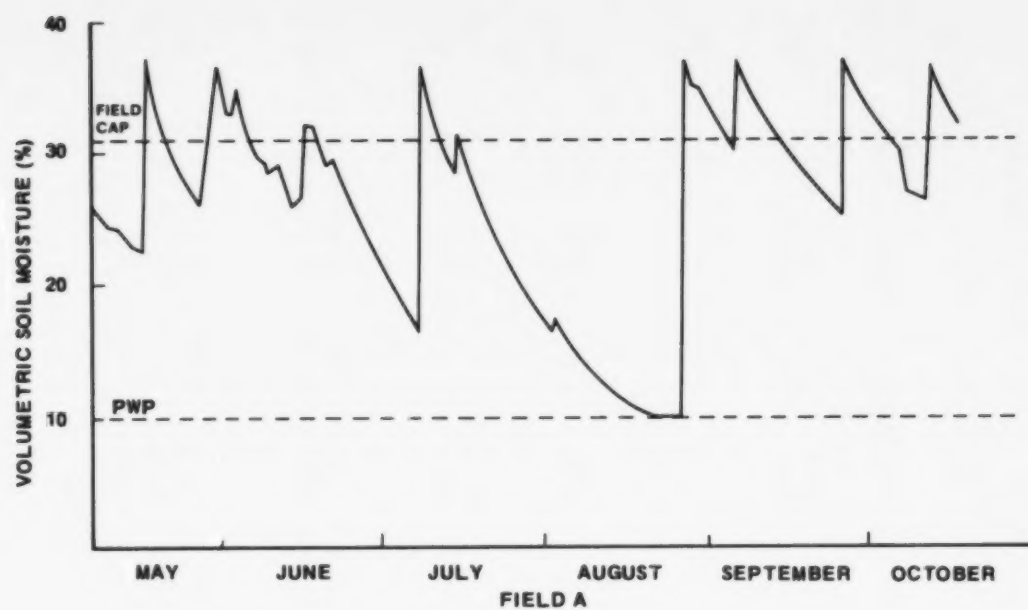
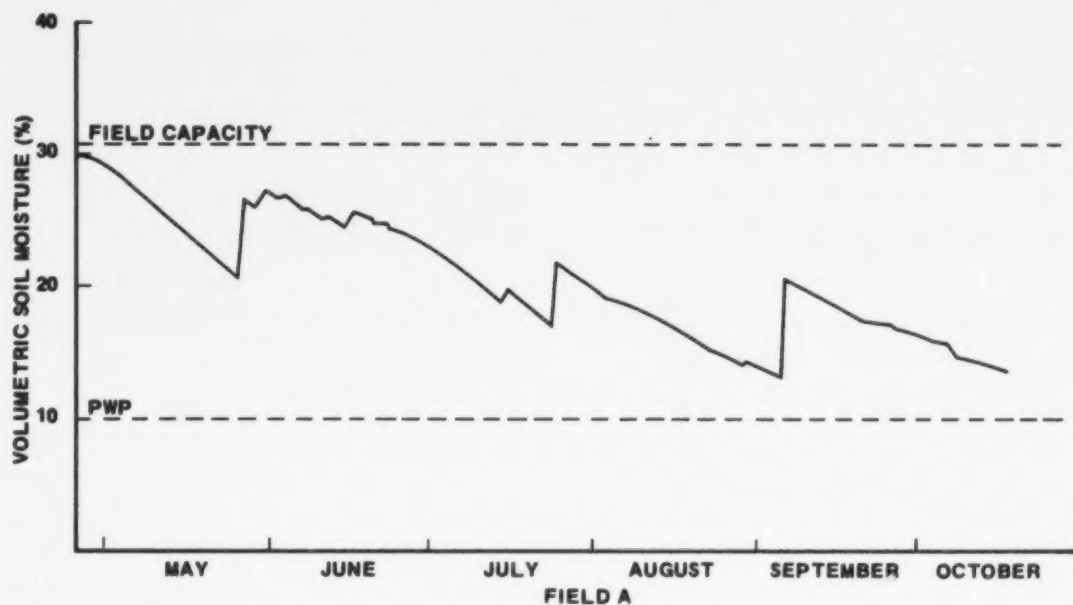


FIGURE 19. Soil moisture histories for two fields.



SOIL MOISTURE HISTORY, FARM 1, FIELD 3, 1964

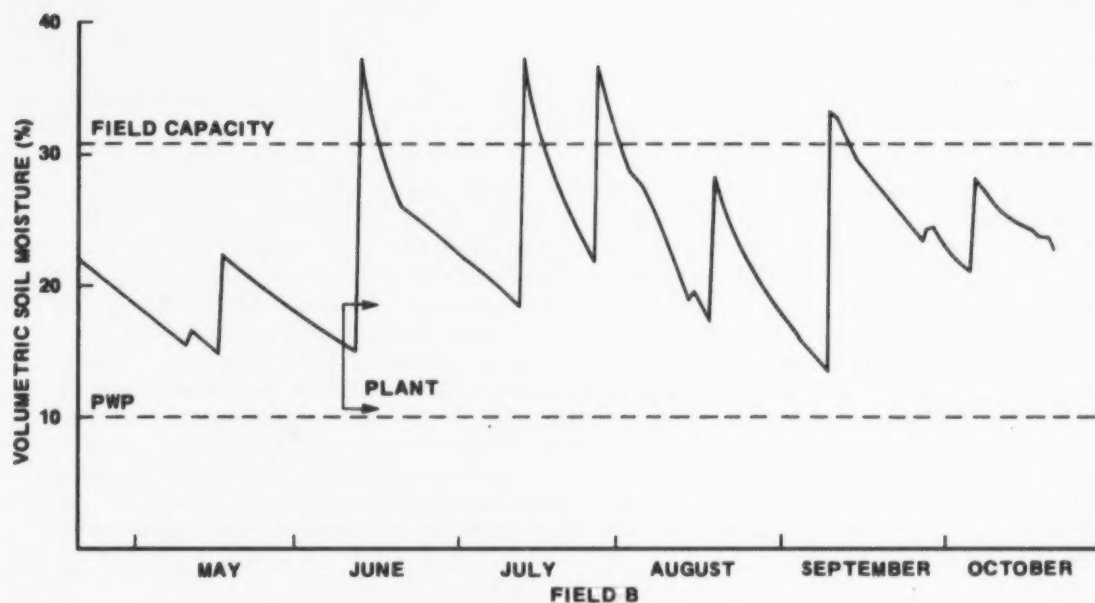


FIGURE 20. Soil moisture histories for two fields.

moisture levels would be either consistently high or consistently low, but not usually high and low under the same circumstances, in fact, however, it was common to see simultaneously very high and very low estimated soil moisture levels within similar fields in a single season.

TABLE 14. NUMBER OF IRRIGATIONS, BY CROP, SCHEDULED AND UNSCHEDULED REGIMES FOR 204 FIELDS

	Unscheduled	Ideal Schedule	Imperfect Schedule
Alfalfa	88	54	52
Barley	58	40	39
Beans	313	212	177
Clover	4	8	6
Pasture	16	32	27
Peas	157	86	85
Potatoes	143	148	123
Wheat	55	35	34
Beets	123	110	100
Wheat & Barley	41	31	31
Winter Wheat	49	28	26
Winter Wheat & Barley	3	2	2
TOTALS	1,050	786	702

The estimated soil moisture content just prior to an irrigation was often found to vary from quite high to quite low. Figure 21 is a histogram of soil moisture just prior to irrigation for 350 irrigation events in 53 bean fields. If properly timed, irrigation events would have been taking place at a soil moisture level of about 21 percent, but in fact they were almost equally likely to take place at any moisture level between the permanent wilting point and the maximum holding capacity of the soil. Eight percent of these irrigations were done when the estimated soil moisture was near the permanent wilting point and another 9 percent were done at about the time when gravity drainage from preceding irrigations ceased. These observations about unscheduled, i.e., historical, irrigation practices must be qualified by the remark that they are based upon model estimates of soil moisture. Only one soil moisture measurement was taken in each case, early in the growing season.

Figure 22 graphically illustrates the changes that could have been brought about by a scheduling service in two fields. In both fields the

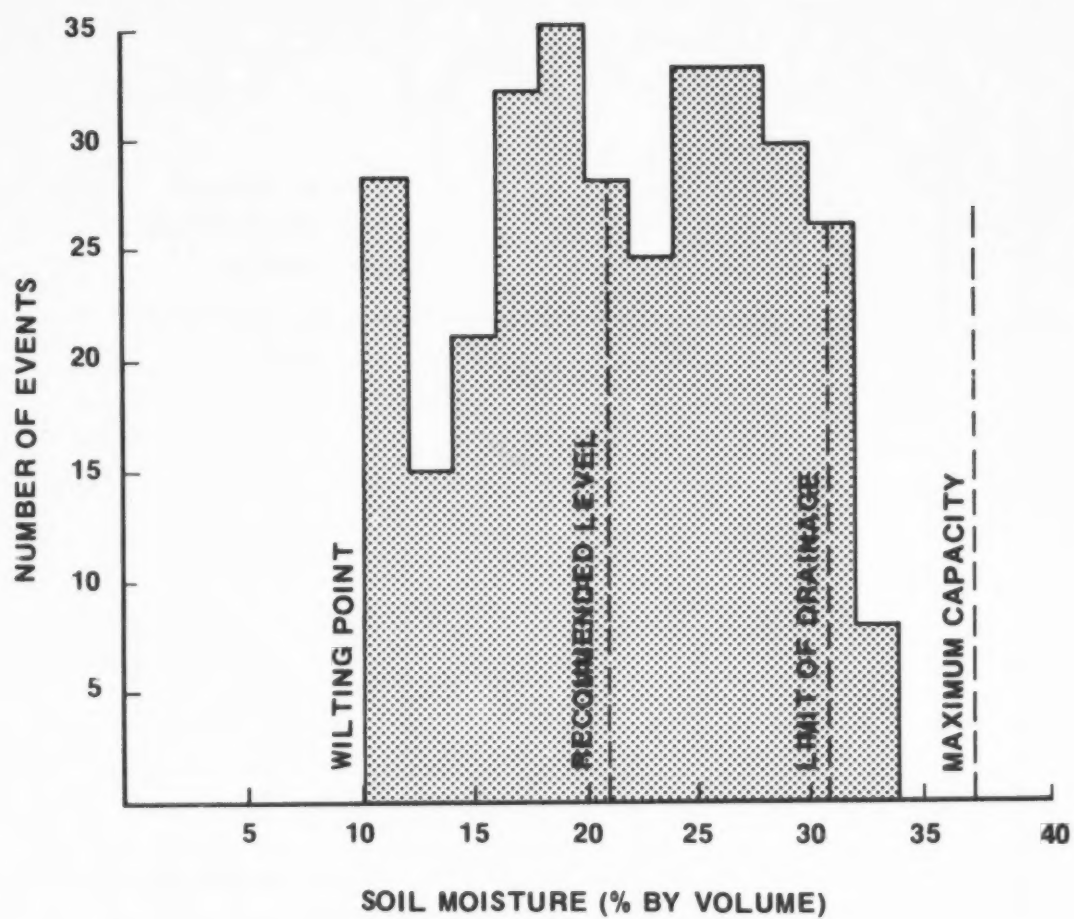


FIGURE 21. Histogram of soil moisture at time of irrigation for 350 irrigation events in bean fields.

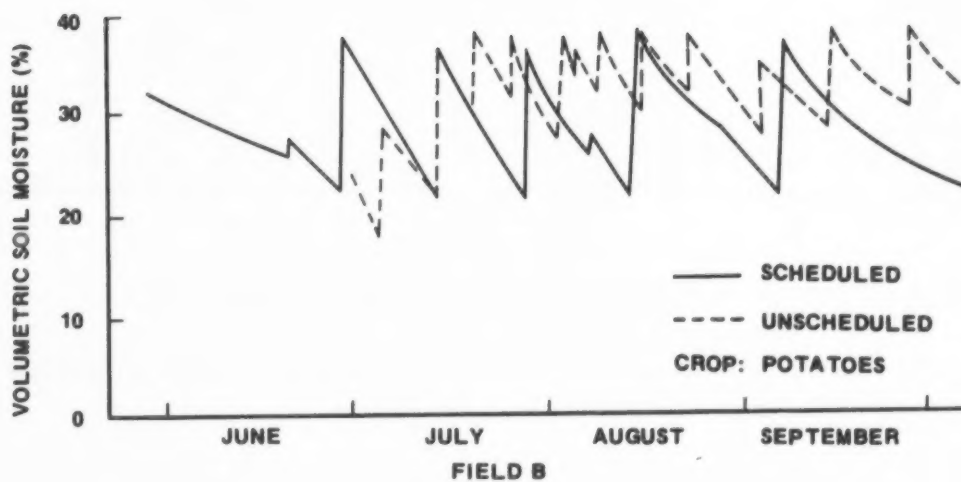
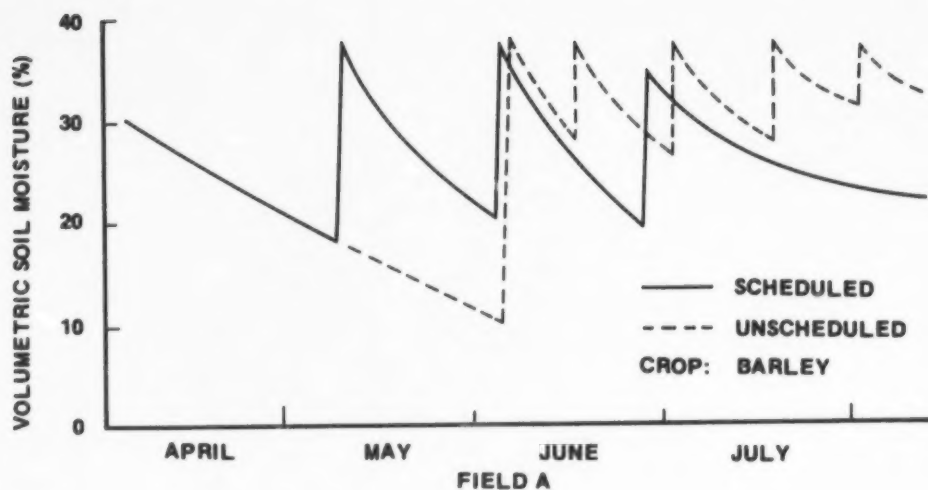


FIGURE 22. Soil moisture histories of two fields with and without the effects of an ideal irrigation scheduling service.

farmers irrigated more frequently and applied far more water than was necessary. Thus, a substantial reduction in drainage and a small reduction in runoff were possible. The barley field also had a very uneven soil moisture history. By scheduling that field the average soil moisture would have changed very little, but much more consistent moisture conditions would have resulted.

Crop Production

Changes in crop yields due to irrigation scheduling were of particular interest in this analysis, since farmers' willingness to use a scheduling service will be largely determined by prospects of improved yields. Two approaches to estimating yields for the scheduled regimes vis-a-vis the unscheduled regime were taken. In the first approach a semi-empirical crop production model was developed and calibrated for each crop with data from the 204 cases of the six-farm study. The second approach was to use a set of estimated yield changes published by the USBR that were derived from a recent study (Table 15, USBR, 1972). Both yield estimates were used in the analysis as alternative scenarios. In one scenario (based on model estimates), modest yield increases were estimated, while in the alternative scenario (based on USBR estimates) considerably larger increases were generally anticipated.

TABLE 15. ESTIMATED CHANGES IN YIELDS IN THE A AND B DISTRICT WITH IRRIGATION SCHEDULING

Crop	EPA/USDA Estimates for 204 Cases	USBR* Estimates
Small Grains	+6.2%	+24.0%
Beans	-2.6%	+12.0%
Peas	-4.8%	+31.0%
Potatoes	+29.3%	+22.0%
Sugar Beets	+15.1%	+12.0%
Alfalfa	+5.9%	+13.0%

*Source: USBR, 1974

The estimated yield changes from the model developed for this analysis should be regarded as indicative of potential changes rather than as conclusive estimates of changes. These numbers represent the estimated cumulative effects of a number of changes in root zone environment which would occur as a result of irrigation scheduling.

The alternative set of yields estimate (USBR) were derived from a study of scheduled fields in the A and B District which was conducted between 1969 and 1971 by the USBR. Measured yields from a group of farms utilizing the scheduling service were compared with district average yields. Yield differentials were adjusted to account for differences in management ability.

The changes in Table 15 refer only to yield changes estimated by these two approaches. However, it is to be expected that irrigation scheduling will also affect crop quality. The qualities of most of the crops in this analysis are affected by soil moisture in various ways. This is especially true of potatoes, for which quality is very adversely affected by stress at critical times. Furthermore, in the case of potatoes, the income received from a crop is more dependent on quality than on total yield.

SECTION 7

REGIONAL ECONOMIC MODEL

A scheduling service can be made available to farmers either by a private company or a public agency. The public agency may choose to offer such a service for many reasons, such as to promote more efficient water use in order to increase the size of a service area from a fixed supply of water, or to reduce irrigation return flows. The purpose of this analysis is to project the amount of irrigation activity that would be scheduled by simulating the economic conditions that would exist if a private company or public agency provided the service. This section contains the theoretical basis for projecting the demand for a scheduling service, the empirical model and the results.

DERIVED DEMAND FOR RESOURCES

The profit maximizing combination of production and resource use for the farmer can be derived by first defining the production function as:

$$Q = f(X_1, X_2, \dots, X_j, \dots, X_n) \quad (21)$$

where Q is an output and X_j are resources. The production function represents the technological process by which the maximum amount of Q can be produced from the specified units of resources. It is assumed that all alternative combinations of inputs to maximize the production of Q are identified in the production function.

The objective of the firm is to maximize profits from the sale of the outputs they produce. The firm will maximize profits by producing a given level of output (Q^*) at a minimum of cost. This can be represented by:

$$C = P_1 X_1 + P_2 X_2 + \dots + P_j X_j + \dots + P_n X_n \quad (22)$$

where C represents the total cost of producing Q^* and P_j are prices for resources X . The production function (21) can be rewritten to represent the physically efficient set of resources to produce a given level of output as:

$$f(X_1, X_2 \dots X_n) - Q^* = 0 \quad (23)$$

and if multiplied by the artificial variable λ , the Lagrangian expression representing a constrained minimization problem can be formed.

$$L = P_1 X_1 + P_2 X_2 + \dots + P_n X_n + \lambda [f(X_1, X_2, \dots, X_n) - Q^*] \quad (24)$$

L is minimized by setting each partial derivative equal to zero.

$$\begin{aligned} \frac{\partial L}{\partial X_1} &= P_1 + \lambda \frac{\partial f}{\partial X_1} = 0 \\ \frac{\partial L}{\partial X_2} &= P_2 + \lambda \frac{\partial f}{\partial X_2} = 0 \\ &\dots \dots \dots \\ \frac{\partial L}{\partial X_n} &= P_n + \lambda \frac{\partial f}{\partial X_n} = 0 \end{aligned} \quad (25)$$

$$\frac{\partial L}{\partial \lambda} = f(X_1, X_2, \dots, X_n) - Q^* = 0$$

This system of $n + 1$ simultaneous equations can be solved for the optimal values of input, variables $X_1 - X_n$ and the value of the Lagrangian variable λ . The marginal condition for optimal use of any resource is:

$$P_j = \lambda \frac{\partial f}{\partial X_j} \quad (26)$$

which states that the value of the marginal product of X_j must equal the price of the resource. The value of λ is the output price and the partial derivative represents the marginal physical product of resource X_j .

The demand for resources is determined by solving Equation 25 for X_j . the implicit demand function can be expressed as:

$$X_j = f(P_j, P_1, \lambda, K) \quad (27)$$

where the amount of X_j used in the production process depends on the price of resource j , the price of substitutable resource, the value of the output and the amount of fixed resources (K).

DERIVED DEMAND FOR IRRIGATION SCHEDULING SERVICES

The demand function for a scheduling service will relate the number of acres (hectares) scheduled to varying prices. Farmers will decide whether or not to schedule fields on the basis of anticipated effects on total returns

*For more detail see Heady and Tweeten (1963).

and total costs. If a larger number of scheduled acres (hectares) adds more to gross returns than to costs, increasing irrigation scheduling will increase net returns. A farmer should schedule that number of acres (hectares) such that the last acre (hectare) scheduled contributes equally to gross receipts and costs if he is to maximize net returns.

The value of marginal product (VMP) of irrigation scheduling is the incremental increase in net market value of crop production as the farmer increases the scheduled land area by one acre (hectare). This value changes as the absolute number of acres (hectares) scheduled increases. On any given farm, irrigation scheduling applied to a given crop and soil type may increase net returns either through increased yields or decreased irrigation costs. However, as subsequent acres (hectares) are scheduled the increases in net returns become smaller because increases in crop yields are smaller or water savings are less. To maximize net returns, the number of acres scheduled should be increased to the level at which the VMP of the last acre (hectare) is equal to the cost of scheduling that acre. This can be written as:

$$VMP_s = P_s \quad (28)$$

where P_s is the cost of scheduling per acre (hectare). The demand curve for scheduling depicts the number of acres (hectares) scheduled as the cost (P_s) varies assuming the condition for profit maximization is met.

In the case of irrigated agriculture, as the price of one variable resource changes the amount of other variable resources will also change as the farmer attempts to find the least cost combination of resources and to maximize net returns. Irrigation water (w), irrigation labor (l), and scheduling are substitutes for each other within a specified range of use. For example, an increase in the price of irrigation water provides an incentive for farmers to use either more labor or a scheduling service to save water. Ideally farmers should employ levels of all these variable resources such that the value of marginal product equals price for each. Therefore, the profit maximizing conditions are:

$$\begin{aligned} VMP_s &= P_s \\ VMP_l &= P_l \\ VMP_w &= P_w \end{aligned} \quad (29)$$

The effect of changes in the cost of scheduling, P_s , upon the number of acres (hectares) scheduled is graphically illustrated in Figure 23. The slope of the line WS represents the price ratio of water and scheduling. The line WS also represents those quantities of water and scheduling that can be purchased by a fixed capital expenditure. If the cost of scheduling increases, the line will shift to WS' to reflect the new price ratio and the new amounts of water and scheduling that the same level of expenditures will purchase.

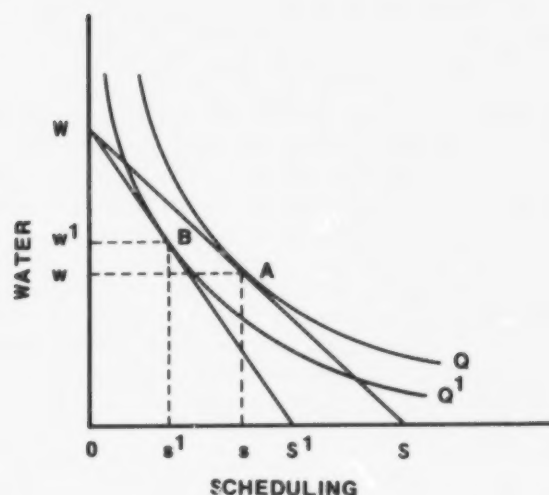


FIGURE 23. Output and substitution effects of a rise in the cost of scheduling.

The quantity of production is represented in Figure 23 by the isoquants Q and Q^1 . A single isoquant reflects one level of output and isoquants further from the origin represent greater levels of production. Therefore the optimum level of production using the amount of water and scheduling represented by the input-price line WS is isoquant Q where WS and Q are tangent. The optimal amount of scheduling use is Os and the optimal amount of water use is Ow . If the cost of scheduling rises, the input-price line shifts to WS^1 and production decreases from A to B . The optimum level of water and scheduling use is Ow^1 and Os^1 . Therefore the change in scheduling use due to the cost change is a decrease from s to s^1 while water use increased from w to w^1 .

The regional demand for a scheduling service can be derived by summing horizontally each farmer's demand for a scheduling service. In other words, the amount of scheduled acres (hectares) at each cost is the sum of all acres (hectares) scheduled by each farmer at that cost. Graph A in Figure 24 represents the demand for scheduling of a typical farmer as previously determined and graph B represents the summation of all farmers in the region for the scheduling service.

REGIONAL LINEAR PROGRAMMING MODEL

Linear programming (LP) is an analytical method that can derive the optimal cropping pattern, irrigation water use, labor use and scheduling service given a set of input-output coefficients, prices and costs. In the previous discussion a number of assumptions were made. First, the production function, i.e., the relationship between resource use and output, is assumed

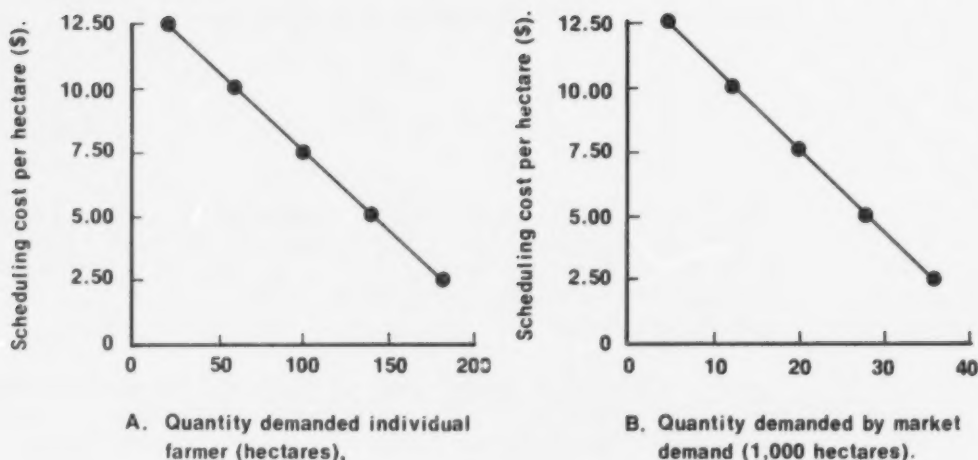


FIGURE 24. Aggregation of individual demand.

to be continuous and single valued. Second, the farmer is aware of all the resource substitution possibilities and he has the power to change the resource mix. Third, the farmer is a profit maximizer. Fourth, the farmer cannot affect the price of commodities or inputs. To frame the problem in the context of linear programming an additional assumption may be made. The continuous production function must be replaced with a collection of independent linear production activities. Each activity represents a specific production-input relationship. The assumption is not critical to the analysis because many activities can be specified to represent the fundamental characteristics of the production function.

The objective function of the linear programming model is:

$$\text{Maximize } f(c) = CX \quad (30)$$

where C is an n dimension row vector representing net revenues and X is an n dimensional column vector representing levels of crop production, commodity selling and resource use. The constraints are:

$$\begin{aligned} AX &\leq B \\ \text{All } X &\geq 0 \end{aligned} \quad (31)$$

where A is an $m \times n$ matrix of resource use coefficients and B is a m dimensional column vector of resources available.

For every linear programming model that exists, a dual problem can be formulated. The dual of this problem is:

$$\text{Minimize } f(u) = UB' \quad (32)$$

where U is a m dimensional row vector representing the inputed value of the firms resources represented by the m dimensional column vector B . The solution is subject to:

$$\begin{aligned} A'U &\geq C' \\ U &\geq 0 \end{aligned} \quad (33)$$

where A' is a $n \times m$ matrix of resource use coefficients and C is a n dimensional column vector of net revenues. The constraints of the dual state that the input costs of producing each output cannot be less than the value of the product. Therefore the value of a resource, such as an irrigation scheduling service, can be estimated for any level of service available.

The specific linear programming model used to analyze irrigation scheduling in the A and B District maximized returns to land, management and risk subject to the usual constraints and some specific resource constraints. Specifically:

$$\begin{aligned} \text{Maximize } Z = & \sum_{j\ell} C_{j\ell} X_{j\ell} + \sum_j P_j S_j - W_a F - W_3 F_3 - W_4 F_4 \\ & - W_5 F_5 - RL - DI \end{aligned} \quad (34)$$

where:

- Z is returns to land, management and risk.
- $C_{j\ell}$ is the cost of producing one acre (.4 ha) of crop j using water application rate ℓ (cost excludes irrigation water, labor and scheduling).
- $X_{j\ell}$ is acreage (hectares) of crop j produced using water application rate ℓ .
- P_j is market price of crop j per unit of yield.
- S_j is amount of crop sold.
- W_a is cost of the first 3 acre-feet ($3.67 \times 10^3 \text{ cm}^3$) of water per acre (.4 ha).
- F is the acreage (hectares) of irrigated crops.
- W_3 is the cost of the fourth acre-foot/acre ($4.93 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) of water applied.
- F_3 is the number of acres (.4 ha) on which four acre-foot/acre ($4.93 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) of water is applied.
- W_4 is the cost of the fifth acre-foot/acre ($6.17 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) of water applied.
- F_4 is the number of acres (.4 ha) on which a five acre-foot/acre ($6.17 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) of water is applied.
- W_5 is the cost of more than five acre-foot/acre ($6.17 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) of water applied.

- F_5 is the number of acres on which greater than five acre-foot/acre ($6.17 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) of water is applied.
 R is the cost of irrigation labor per hour.
 L is the total irrigation labor used.
 D is the cost of irrigation scheduling per acre (.4 ha).
 I is the irrigated acreage (hectares) scheduled.

The objective function is subject to the following constraints:

$$\sum_{jl} X_{jl} \leq A \quad (35)$$

where A is the total acreage (hectares) of land in the District.

$$\sum_{jl} -y_{jl} X_{jl} + S_j \leq 0 \quad (36)$$

where y_{jl} is crop j yield per acre (.4 ha) when water application is l ,

$$\sum_{jl} X_{jl} - F \leq 0 \quad (37)$$

represents the total irrigated acreage (hectares) in the District.

$$\sum_{jl} a_{jl}^3 X_{jl} - F_3 \leq 0 \quad (38)$$

where a_{jl}^3 is the crop water requirement in excess of 3 acre-feet/acre ($3.67 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) (1 if in excess of 4 acre-feet/acre ($4.93 \times 10^3 \text{ cm}^3/.4 \text{ ha}$)) for crop j and water application l ,

$$\sum_{jl} a_{jl}^4 X_{jl} - F_4 \leq 0 \quad (39)$$

where a_{jl}^4 is the crop water requirement in excess of 4 acre-feet/acre ($4.93 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) (1 if in excess of 5 acre-feet/acre ($6.17 \times 10^3 \text{ cm}^3/.4 \text{ ha}$)) for crop j and water application l ,

$$\sum_{jl} a_{jl}^5 X_{jl} - F_5 \leq 0 \quad (40)$$

where a_{jl}^5 is the crop water requirement in excess of 5 acre-feet/acre ($6.17 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) for crop j and water application l ,

$$\sum_{jl} a_{jl} X_{jl} \leq E \quad (41)$$

where a_{jl} is the total water requirement for crop j at water application rate l and E is the total District water supply,

$$\sum_{jl} g_{jl} X_{jl} - L \leq 0 \quad (42)$$

where g_{jl} is the irrigation labor requirement for one acre (.4 ha) of crop at water application rate l ,

$$\sum_{jl} X_{jl} \leq Z_j \text{ for all } j \quad (43)$$

where Z_j is a crop acreage (hectare) limit that reflects historical crop acreage,

$$\sum_{jl} r_{jl} X_{jl} \geq 0 \quad (44)$$

where r_{jl} is the surface runoff from one acre (.4 ha) of crop j at water application rate l ,

$$\sum_{jl} p_{jl} X_{jl} \geq 0 \quad (45)$$

where p_{jl} is the deep percolation from one acre (.4 ha) of crop j at water application rate l ,

$$\sum_{jl} d_{jl} X_{jl} \geq 0 \quad (46)$$

where d_{jl} is the sediment loss from one acre (.4 ha) of crop j at water application rate l ,

$$\sum_{jl} s_{jl} X_{jl} \geq 0 \quad (47)$$

where s_{jl} is the salinity loss from one acre (.4 ha) of crop j at water application rate l , and,

$$\sum_j X_j - I \leq 0 \quad (48)$$

represents the total acres (hectares) of scheduled irrigation.

The linear programming model for the A and B Irrigation District is presented in matrix form in Figure 25. This matrix illustrates the model structure and assists in describing how the analysis was conducted. The derived demand for a resource can be empirically estimated by parametrically varying the cost of scheduling through the possible range and observing the optimal number of acres being scheduled. This procedure provides the necessary information to construct a static-normative demand function (Moore

ACTIVITIES				CROP PRODUCTION					COMMODITY SELLING	IRRIGATED ACRES	WATER SUPPLY			IRRIGATION LABOR	IRRIGATION SCHEDULING
Row Name	RHS	Type	Maximize C =	Water Application Rate			Scheduled	Price per Unit of Yield	-Cost per acre	Third AF/Acre -Cost for Third AF	Fourth AF/Acre -Cost for Fourth AF	>Four AF/Acre -Cost for >4 AF	-Wage Rate	-Scheduling Cost	
				Low	Medium	High									
								-Cost of Production Per Acre							
1. Land	Acres	N		1	1	1	1								
2. Commodity Yield	0	N		-y	-y	-y	-y	1							
3. Irrigated Acres	0	N		1	1	1	1		-1						
WATER:															
4. Third AF/A	0	N		a ³	a ³	a ³	a ³			-1					
5. Fourth AF/A	0	N		a ⁴	a ⁴	a ⁴	a ⁴				-1				
6. >Four AF/A	0	N		a ⁵	a ⁵	a ⁵	a ⁵					-1			
7. Supply	AF/Year	N		a	a	a	a								
8. Irrigation Labor	0	N		g	g	g	g						-1		
9. Cropping Pattern	Acres	N		1	1	1	1								
10. Surface Runoff	0	VI		r	r	r	r								
11. Deep percolation	0	VI		p	p	p	p								
12. Sediment	0	VI		d	d	d	d								
13. Salinity	0	VI		s	s	s	s								
14. Scheduling	0	N					1							-1	
				1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	

FIGURE 25. A and B District linear programming model.

and Hedges). The same demand function could be constructed by parametrically varying the level of scheduling services and observing the value of the dual activity or value of the resource related to the constraint. In addition, the LP model provides estimates of the amount of and quality of return flows, irrigation water use and irrigation labor that are essential for a complete evaluation of a scheduling program.

The LP model was optimized for three configurations. The first solution was constrained to unscheduled operations to estimate the level of returns to producers, resource use and irrigation return flows assuming a scheduling service did not exist. This solution served as a basis to which other solutions could be compared. The second model configuration required all water applications to be determined by a scheduling service. The difference between the solutions derived in the first and second model configurations served as a estimate of the potential change that could be possible from a scheduling service.

The third configuration was not restricted to the scheduled or non-scheduled water applications. Therefore, the optimal solution represented the level of scheduling that would probably exist if the service were offered on a profit or nonprofit basis. The cost of the scheduling service and the cost of water were parameterized in the third model configuration to determine the effect on the amount of scheduled acres.

Input Data

The analysis of USBR data produced a combined set of both real and estimated data which related water use to crop yields and irrigation return flows. These data were used, together with price and cost data, to derive the regional coefficients required for the linear programming model. The procedures for deriving water application rates, labor requirement, crop yields, crop prices, production costs and returns to land, management and risk are described in the following sections.

Water Application Rates--

Three levels of irrigation water application were defined as low, medium and high on the basis of observed water use by crop in 443 unscheduled field operations in the A and B District. The 443 cases were from the 6 farm study (204 cases) and the 40 farm study (239 cases) and included corresponding crop yields. Table 16 contains the specific water application rate and the proportion of cases in each rate. As an example, the range between 25 and 35 inches (63.5 and 88.9 cm) of applied water was defined as medium water use for barley. Less than 25 inches (63.5 cm) and more than 35 inches (88.9 cm) were defined as low and high water use, respectively.

Irrigation Labor--

The average irrigation labor per acre (.4 ha) per set and the average number of irrigation sets for each crop were estimated from the six-farm study and were used to compute the average total irrigation labor per acre (.4 ha) by crop for each water application rate (Table 17). Substantial labor savings could be realized by using a scheduling service for most crops.

Labor requirements could be reduced for peas by 46 percent, alfalfa 44 percent, wheat 41 percent and beans 39 percent.

TABLE 16. DEFINITION OF LOW, MEDIUM AND HIGH WATER-USE (UNSCHEDULED IRRIGATION REGIME) AND PROPORTION OF IRRIGATED CASES IN EACH CATEGORY

Crop	Low	Medium	High
	acre-inch/year or 1.028 ha-cm/year*		
Alfalfa	0 - 35.1 (0.243)**	35.1 - 50.0 (0.457)	> 50 (0.300)
Barley	0 - 25.03 (0.541)	25.04 - 35.0 (0.360)	> 35.0 (0.099)
Beans	0 - 25.0 (0.255)	25.0 - 37.0 (0.568)	> 37.0 (0.177)
Peas	0 - 27.0 (0.452)	27.0 - 42.0 (0.474)	> 42.0 (0.074)
Potatoes	0 - 30.0 (0.115)	20.0 - 45.0 (0.499)	> 45.0 (0.386)
Sugar Beets	0 - 40.1 (0.346)	40.1 - 50.0 (0.414)	> 50.0 (0.240)
Wheat	0 - 25.0 (0.544)	25.0 - 35.0 (0.364)	> 35.0 (0.092)

*Acre-inches/year = 1.028 ha-cm/year. Therefore 35.1 acre-inches/year = 36.1 ha-cm/year.

**Numbers in parenthesis represent the proportion of fields of a crop that were irrigated with the respective amount of water.

Crop Yields--

Crop yields observed on the 443 water use cases were used to estimate yields for each crop for each level of unscheduled water use. Crop yields had to be adjusted to reflect technologic changes that have caused gradual increases in crop yields. Trend lines were derived using regression analysis on the 443 average yields for the years 1958 through 1975. The equations of these trend lines for barley, potatoes, wheat and alfalfa were estimated and used to adjust yield predictions to more accurately reflect yields in the years 1973, 1974 and 1975, the years for which the case study analysis was done (Table 18). Additionally, average yields from the six-farm study were found to be significantly higher than district average yields for the same years. Therefore, yields derived from the six-farm study had to be adjusted to represent aggregate district yields. Alternative crop yields for the ideal scheduling regime, one based upon the USBR estimates of yield increases and the other based upon the EPA/USDA estimates (Table 18). Fertilization rates were not significantly different for the three water application rates.

TABLE 17. WATER APPLICATION RATES, LABOR REQUIREMENTS AND CROP YIELDS, A & B DISTRICT

Crop	Water Application	Water Applications Range	Average Acre-in/year or 1.028 ha-cm/year	Average Number of Sets	Labor Requirement Per Set	Total Irrigation Labor	Yields	
							Unscheduled	Scheduled
					Hours/Acre or hours/.4 ha*		EPA/USDA	USBR
							Tons/Acre or .907 Metric Tons/.4 ha	
Alfalfa	low	0-35	28.52	3.6	.365	1.31	4.56	
	medium	35-40	42.62	4.2	.379	1.59	4.25	
	high	>50	64.24	4.4	.381	1.68	5.2	
	scheduled (ideal)		42.00	2.45	.376	.92		4.87
	scheduled (imperfect)		50.76	2.36	.376	.89		5.01
Barley	low	0-25	20.5	3.7	.361	1.34	Bushels or 63.33 kg/.4 ha	
	medium	25-35	28.1	3.8	.372	1.41	87.58	
	high	>35	39.6	5.7	.371	2.11	90.98	
	scheduled (ideal)		17.76	2.73	.367	1.0	86.88	
	scheduled (imperfect)		24.96	2.77	.367	1.02	90.48	98.74
Beans	low	0-25	21.85	6.2	.343	2.13	cwt./acre or 45.36 kg/.4 ha	
	medium	25-37	30.95	6.8	.35	2.38	19.3	
	high	>37	46.54	6.5	.364	2.37	18.6	
	scheduled (ideal)		19.44	4.93	.35	1.73	19.3	
	scheduled (imperfect)		30.24	4.12	.35	1.44	20.27	23.28

Continued --

TABLE 17.--CONTINUED

Crop Water Application	Water Applications Range	Average Number of Sets	Labor Requirement Per Set	Total Irrigation Labor	Yields	
					Unscheduled	Scheduled
					EPA/USDA	USBR
	Acre-in/year or 1.028 ha-cm/year		Hours/acre or hours/.4 ha*			
Peas					cwt./Acre or 45.26 kg/.4 ha	
low	0-27	19.76	.348	1.53	19.92	
medium	27-42	34.37	.36	1.66	25.62	
high	>42	46.43	.35	2.14	24.42	
scheduled (ideal)		17.28	.354	.9		22.7
scheduled (imperfect)		23.16	.354	.89		26.66
Potatoes					Tons/Acre or 45.36 kg/.4 ha	
low	0-30	27.07	.342	2.22	224.60	
medium	30-45	37.6	.344	2.58	235.1	
high	>45	51.64	.357	2.71	212.1	
scheduled (ideal)		24.12	.345	2.55		244.2
scheduled (imperfect)		30.72	.345	2.12		261.09
Sugar Beets					Tons/Acre or .907 Metric Tons/ Acre	
low	0-40	35.63	.351	2.6	17.99	
medium	40-50	45.13	.347	2.64	17.19	
high	>50	57.22	.381	2.25	17.49	
scheduled (ideal)		27.36	.355	2.07		18.21
scheduled (imperfect)		32.88	.355	1.87		19.84

Continued --

TABLE 17.--CONTINUED

Crop Water Application	Water Applications Range	Average Acre-in/year or 1.028 ha-cm/year	Average Number of Sets	Labor Requirement Per Set	Irrigation Labor	Yields	
						Unscheduled	Scheduled
						EPA/USDA	USBR
					Hours/Acre or hours/.4 ha*		
Bushel/Acre or 66.67 kg/.4 ha							
Wheat							
low	0-25	22.2	3.1	.364	1.13	85.2	
medium	25-35	30.02	4.1	.358	1.47	39.4	
high	>35	50.21	8.0	.35	2.8	85.9	
scheduled		17.28	2.5	.36	.9		96.64
(ideal)							
scheduled		28.44	2.43	.36	.87		
(imperfect)							

80 *To convert labor requirement in hours per acre to hours per hectare, multiply the hours/
acre x 2.471.

TABLE 18. CROP YIELD TREND EQUATIONS FOR
THE A AND B IRRIGATION DISTRICT

Crop	Trend Equation
Alfalfa	$y^* = 2.67 + .029$ (3.06) + (2.24)†
Barley	$y = -32.4 + 1.68t$ (-1.72) (5.94)
Potatoes	$y = 79.5 + 2.03t$ (1.18) (2.01)
Spring Wheat	$y = -36.0 + 1.65t$ (-1.23) (3.73)

*y = yield and t = year

†Number in parenthesis are t values where

t = $\frac{\text{regression coefficient}}{\text{standard error of the regression coefficient}}$

Crop Prices and Production Costs--

Crop prices used in the analysis were district average prices paid to farmers in the A and B District during the years 1973 through 1975 (Table 19). Water costs were based upon actual District costs during those same years (Table 20). Production costs per acre (.4 ha) for alfalfa, barley, potatoes, sugar beets, and spring wheat were based on variable preharvest costs taken from budgets derived by Kuntz, 1976 (Table 21). Harvest costs were adjusted proportionally for the differences between the yield per acre (.4 ha) used in the budget and the yield per acre (.4 ha) adjusted for trend. The production costs for dry beans and dry edible peas were derived from costs supplied by the University of Idaho's Cooperative Extension Service. Wage rates for irrigators were \$3.04/hour, \$3.50/hour, and \$3.82/hour in 1973, 1974, and 1975, respectively. A substantial increase in production costs were experienced between 1973 and 1975 (Table 21). Increase in alfalfa production costs for example were 23 percent for medium water applications from 1973 to 1975. The percentage increase in costs, resulting from general cost increases in all factors of production, except irrigation water costs, were very similar for most other crops grown in the A and B District. Production costs are also estimated for a scheduling service assuming the crop yields that the USBR obtained from their studies.

Returns to Land, Management and Risk by Amount of Water Application

Gross returns were calculated from crop yields and commodity prices by water application for 1973, 1974 and 1975 (Table 22). Returns to land, management and risk were estimated by subtracting the production costs listed in Table 21. The returns are so defined because the payments for land use and production management and explicit consideration for the effects

TABLE 19. AVERAGE COMMODITY PRICES
A & B DISTRICT: 1973-1975

	1973	1974	1975
Alfalfa (\$/ton or .907 metric tons)	45.00	40.00	45.00
Barley (\$/bu or 63.33 kg)	2.28	3.00	2.21
Beans (\$/cwt or 45.36 kg)	23.00	24.50	15.75
Peas (\$/cwt or 45.36 kg)	5.50	17.00	14.50
Potatoes (\$/cwt or 45.36 kg)	3.55	4.10	3.15
Sugar Beets (\$/ton or .907 metric tons)	17.35	31.50	25.70
Wheat (\$/bu or 66.67 kg)	4.50	4.10	3.00

TABLE 20. IRRIGATION WATER COSTS, A & B
DISTRICT, 1973, 1974, and 1975

<u>Water Delivered</u>	<u>Cost</u>		
	1973	1974	1975
		\$	
First 3 acre-feet ($3.67 \times 10^3 \text{ cm}^3/.4 \text{ ha}$)	9.25	10.00	10.00
Fourth acre-foot ($4.93 \times 10^3 \text{ cm}^3/.4 \text{ ha}$)	3.22	3.45	3.69
Fifth acre-foot ($6.17 \times 10^3 \text{ cm}^3/.4 \text{ ha}$)	4.77	5.55	5.90
Subsequent deliveries per acre-foot ($1.233 \times 10^3 \text{ cm}^3/.4 \text{ ha}$)	6.44	6.94	7.38

Source: A & B Irrigation District, Unpublished records.

of risk are not included in the estimation of production costs. Therefore the returns listed in Table 21 are not "profits" to the farmer but rather income that will cover costs not listed explicitly in the budget. Land costs were not accounted for since a wide variation exists depending on whether the farmer rents, leases, owns, or inherits the property. Management costs were not included because most farmers in the A and B Irrigation District were owner-operators and no universally accepted method exists to separate and evaluate the management effort.

Irrigation Return Flows--

Estimates of surface runoff, deep percolation, sediment loss and TDS were derived for the three unscheduled water application levels and the ideal and the imperfect scheduling regimes from the data and physical models

TABLE 21. CROP PRODUCTION COSTS, 1973, 1974, AND 1975, A AND B DISTRICT

Crop	Water Application	Variable Costs			Irrigation Labor Costs*			Water Costs			Total Production Costs		
		1973	1974	1975	1973	1974	1975	1973	1974	1975	1973	1974	1975
		dollars per acre or .4 ha											
Alfalfa	low	64.18	73.99	80.68	3.98	4.59	5.00	9.25	10.00	10.00	77.41	88.58	95.68
	medium	60.82	70.11	76.45	4.83	5.57	6.07	11.03	11.90	12.04	76.68	87.58	95.56
	high	71.15	82.02	89.43	5.11	5.88	6.42	19.67	21.62	22.38	95.93	109.52	118.23
	scheduled**	67.56	77.88	84.92	2.79	3.22	3.51	10.86	11.73	11.84	81.21	92.83	100.27
	scheduled***	69.08	79.63	86.83	2.79	3.22	3.51	10.86	11.73	11.84	82.73	94.58	102.18
	imperfect schedule	---	---	---	2.71	3.12	3.40	13.57	14.73	15.05	---	---	---
Barley	low	57.47	66.25	72.24	4.07	4.69	5.12	9.25	10.00	10.00	70.79	80.94	87.36
	medium	58.27	67.17	73.24	4.29	4.94	5.39	9.25	10.00	10.00	71.81	82.11	88.63
	high	57.34	66.10	72.07	6.41	7.39	8.06	10.22	11.04	11.11	73.97	84.53	92.24
	scheduled**	58.15	67.03	73.09	3.04	3.50	3.82	9.25	10.00	10.00	70.44	80.53	86.91
	scheduled***	60.70	69.25	75.51	3.04	3.50	3.82	9.25	10.00	10.00	72.36	82.75	89.33
	imperfect schedule	---	---	---	3.10	3.57	3.90	9.25	10.00	10.00	---	---	---
Beans	low	70.33	81.07	88.40	6.48	7.46	8.14	9.25	10.00	10.00	86.06	98.53	106.54
	medium	69.89	80.57	87.85	7.24	8.33	9.09	9.25	10.00	10.00	86.38	98.90	106.94
	high	70.33	81.07	88.40	7.20	8.30	9.05	12.08	13.03	13.24	89.61	102.40	110.69
	scheduled**	70.92	81.76	80.15	5.26	6.06	6.61	9.25	10.00	10.00	85.43	97.82	96.76
	scheduled***	72.78	83.90	91.48	5.26	6.06	6.61	9.25	10.00	10.00	87.29	99.96	108.09
	imperfect schedule	---	---	---	4.38	5.04	5.50	9.25	10.00	10.00	---	---	---

continued

TABLE 21.--CONTINUED

Crop	Water Application	Variable Costs				Irrigation Labor Costs*				Water Costs				Production Costs					
		1973		1974		1975		1973		1974		1975		1973		1974		1975	
		dollars per acre or .4 ha																	
Peas																			
	low	64.89	74.80	81.56	4.65	5.36	5.84	9.25	10.00	10.00	78.79	90.16	97.40						
	medium	68.41	78.87	86.00	5.05	5.81	6.34	9.25	10.00	10.00	82.71	94.68	102.34						
	high	67.67	78.01	85.06	6.51	7.49	8.17	12.05	13.00	13.21	86.23	98.50	106.44						
	scheduled**	66.60	76.77	83.71	2.74	3.15	3.44	9.25	10.00	10.00	78.59	89.92	97.15						
	scheduled***	69.06	79.61	86.80	2.74	3.15	3.44	9.25	10.00	10.00	81.05	92.76	100.24						
	imperfect schedule	---	---	---	2.71	3.12	3.40	9.25	10.00	10.00	---	---	---						
Potatoes																			
	low	202.11	232.99	254.04	6.75	7.77	8.48	9.25	10.00	10.00	218.11	250.76	272.52						
	medium	203.80	234.94	256.17	7.84	9.03	9.86	9.68	10.46	11.11	221.32	254.43	277.14						
	high	203.54	230.64	251.48	8.24	9.49	10.35	13.92	15.13	15.48	225.70	255.26	277.31						
	scheduled**	205.27	236.63	258.01	7.75	8.93	9.74	9.25	10.00	10.00	222.27	255.56	277.75						
	scheduled***	207.99	239.76	261.44	7.75	8.93	9.74	9.25	10.00	10.00	224.99	258.69	281.18						
	imperfect schedule	---	---	---	6.44	7.42	8.10	9.25	10.00	10.00	---	---	---						
Sugar Beets																			
	low	187.25	215.86	235.37	7.90	9.10	9.93	9.25	10.00	10.00	204.40	234.96	255.30						
	medium	185.02	213.29	232.56	8.03	9.24	10.08	11.70	12.63	12.81	204.75	235.16	255.45						
	high	185.86	214.26	233.62	6.84	7.88	8.59	16.13	17.71	18.22	208.83	239.85	260.43						
	scheduled**	187.86	216.56	236.13	6.29	7.26	7.91	9.25	10.00	10.00	203.40	233.82	254.04						
	scheduled***	192.37	221.76	241.80	6.29	7.26	7.91	9.25	10.00	10.00	207.91	239.02	259.71						
	imperfect schedule	---	---	---	5.68	6.55	7.14	9.25	10.00	10.00	---	---	---						

Continued

TABLE 21.--CONTINUED

Crop	Water Application	Variable Costs			Irrigation Labor Costs*			Water Costs			Total Production Costs		
		1973	1974	1975	1973	1974	1975	1973	1974	1975	1973	1974	1975
Wheat													
low		49.87	57.49	62.68	3.44	3.96	4.32	9.25	10.00	10.00	62.56	71.45	77.00
medium		50.87	58.64	63.94	4.67	5.15	5.62	9.25	10.00	10.00	64.79	73.79	79.76
high		50.04	57.68	62.89	8.51	9.80	10.50	13.35	14.47	14.48	71.90	81.95	88.37
scheduled**		50.22	57.89	63.12	2.73	3.15	3.44	9.25	10.00	10.00	62.20	71.04	76.56
scheduled***		52.60	60.64	66.12	2.73	3.15	3.44	9.25	10.00	10.00	64.58	73.79	79.56
imperfect schedule		---	---	---	2.64	3.05	3.32	9.25	10.00	10.00	---	---	---

*Wage rates per hour: 1973, \$3.04; 1974, \$3.50; 1975, \$3.82.

**Production costs based on yields estimated in this study.

***Production costs based on yields estimated by USBR.

Source: Kuntz, 1976. (unpublished data).

TABLE 22. RETURNS TO LAND, MANAGEMENT AND RISK BY AMOUNT OF WATER APPLICATION

Crop	Water Application Rate	Gross Returns		Returns to Land, Management and Risk		
		1973	1974	1975	1973	1974
		Dollars/Acre or .4 ha				
Alfalfa	low	205.20	182.40	205.20	127.79	93.82
	medium	191.25	170.00	191.25	114.57	82.84
	high	234.00	208.00	234.00	138.07	94.48
	scheduled*	219.15	194.80	219.15	137.94	101.97
	scheduled**	225.45	200.40	225.45	142.72	105.82
Barley	low	199.68	262.74	193.55	128.89	181.80
	medium	207.43	272.94	201.07	135.62	190.83
	high	198.09	260.64	192.00	124.12	176.11
	scheduled*	206.29	271.44	199.96	135.85	190.91
	scheduled**	225.13	296.22	218.22	152.77	213.47
Beans	low	443.90	472.85	303.98	357.84	374.32
	medium	427.80	455.70	292.95	341.42	356.80
	high	443.90	472.85	303.97	354.29	370.45
	scheduled*	466.21	496.62	319.25	380.78	389.80
	scheduled**	535.44	570.36	366.66	448.15	470.40
Peas	low	109.56	338.64	288.84	30.77	248.48
	medium	140.91	435.54	371.49	58.20	340.86
	high	134.31	415.14	354.09	48.08	316.64
	scheduled*	124.85	385.90	329.15	46.26	295.98
	scheduled**	146.63	453.22	386.57	65.58	360.46

Continued --

TABLE 22.--CONTINUED

Crop	Water Application Rate	Gross Returns		Returns to Land, Management and Risk		
		1973	1974	1975	1973	1974
		Dollars/Acre		or .4 ha		
Potatoes						
low		797.33	920.86	707.49	579.22	670.10
medium		834.61	963.91	740.57	613.29	709.48
high		752.96	869.61	668.12	527.26	614.35
scheduled*		866.91	1,001.22	769.23	644.64	745.66
scheduled**		926.87	1,070.47	822.34	701.88	811.78
Sugar Beets						
low		312.13	566.69	462.34	107.73	331.73
medium		298.25	541.49	441.78	93.50	306.33
high		303.45	550.94	449.49	94.62	311.09
scheduled*		315.94	573.62	468.00	112.54	339.80
scheduled**		344.22	624.96	509.89	136.31	385.94
Wheat						
low		383.40	349.32	255.60	320.84	277.87
medium		402.30	366.54	268.20	337.51	292.75
high		386.55	352.19	257.70	314.65	270.24
scheduled*		389.97	355.31	259.98	327.77	284.27
scheduled**		434.88	396.22	289.92	370.30	322.43

*Gross returns based on yields estimated in this study.

**Gross returns based on yields estimated by USBR.

discussed earlier (Table 23). For almost all crops grown in the A and B District, the amount of return flows would be reduced and the quality improved by using a scheduling service when compared to the three water application rates. However, a significant difference exists in the estimates of return flows for an ideal or imperfect scheduling regime. The schedule that did not have application errors reduced some return flow parameters even below those levels achieved under low water application rates. In the case of barley, peas and potatoes all parameters were reduced below this level while for beans and sugar beets three parameters were so effected. In the cases where application errors were introduced, the amount and quality of return flows were similar to those that resulted from medium water application rates. TDS and deep percolation were reduced on sugar beets below the levels resulting from low application rates with both scheduling regimes. Return flows from alfalfa were substantially higher from scheduled applications than from unscheduled applications. Typical unscheduled operations tend to under-irrigate alfalfa and therefore substantially reduce return flows.

Historical Cropping Patterns--

The cropping pattern established in the LP model was constrained to those acreages that existed in 1973, 1974, and 1975 in order to focus the analysis on the effects of a scheduling service. If the solution were not constrained, all of the land would be allocated to the most profitable crop making the results unrealistic. Farmers within an area do not plant the most profitable crop in a region for a number of reasons.

First, the element of risk in growing, harvesting and selling a crop plays an important role in the selection of a cropping pattern. To spread the risk, farmers will plant a mixture of crops that are not subject to the same price fluctuations, weather, insect infestations or diseases. Second, decisions on cropping pattern are also made on projected prices rather than current prices and all farmers use various sources of information to determine future profitability. Therefore, it is not uncommon to see varying cropping patterns all based on projected profitability. Third, crop rotations need to be established and continued to maintain the long run soil productivity and to minimize disease and pest damage. Fourth, farmers possess and exhibit preferences for growing specific types of crops. These tendencies may be the result of agronomic expertise, possessing a unique equipment complement or long term marketing arrangements to provide a supply of a particular commodity. Fifth, some crops are contracted and therefore subject to processor capacity and company policy. In the A and B District, sugar beets, potatoes, beans and peas were contracted.

Substantial indepth research on the extent farmers are motivated by factors other than price-cost considerations is required before the appropriate constraints can be placed on the LP solution. Therefore the solution was constrained to the 1973, 1974 and 1975 cropping pattern so that the analysis could be focused on the optimal use of water and a scheduling service.

TABLE 23. VOLUME AND QUALITY OF IRRIGATION RETURN FLOW PER ACRE, A & B DISTRICT

Crop	Water Application	Surface Runoff Acre-in/Acre or 1.03 ha-cm/ha	Deep Percolation	Sediment Loss		Total Dissolved Solids
				Tons/Acre or .907 Metric Tons/.4 ha		
Alfalfa	low	5.22	0.00	.247		.086
	medium	6.29	3.27	.402		.534
	high	14.35	13.68	.528		1.039
	scheduled (ideal)	11.00	2.22	.314		.608
	scheduled (imperfect)	9.72	12.57	.357		1.080
Barley	low	2.45	2.64	.422		.387
	medium	4.35	6.05	.718		.535
	high	9.85	14.62	1.750		.894
	scheduled (ideal)	1.86	2.49	.311		.350
	scheduled (imperfect)	3.33	7.48	.566		.594
Beans	low	4.67	2.24	.522		.311
	medium	6.96	6.86	.731		.565
	high	8.92	16.24	1.214		.929
	scheduled (ideal)	4.09	.96	.645		.260
	scheduled (imperfect)	4.17	4.92	.696		.484
Peas	low	2.86	5.78	.491		.490
	medium	5.11	12.39	.788		.805
	high	10.22	15.11	1.655		.996
	scheduled (ideal)	2.26	1.87	.397		.342
	scheduled (imperfect)	3.59	6.80	.634		.533

Continued--

TABLE 23.---CONTINUED

Crop	Water Application	Surface Runoff Acre-in/Acre or 1.03 ha-cm/ha	Deep Percolation	Sediment Loss Tons/Acre or .907 Metric Tons/.4 ha	Total Dissolved Solids
Potatoes					
low	4.12	5.28	.537	.563	
medium	6.71	11.06	.884	.834	
high	11.62	23.67	1.475	1.454	
scheduled (ideal)	3.60	1.59	.507	.408	
scheduled (imperfect)	5.78	6.69	.807	.652	
Sugar Beets					
low	5.90	6.93	.722	.716	
medium	10.29	10.77	1.268	.830	
high	10.77	22.10	1.464	1.555	
scheduled (ideal)	5.32	2.42	.808	.496	
scheduled (imperfect)	6.25	6.63	.942	.704	
Wheat					
low	2.15	2.17	.462	.395	
medium	5.89	9.31	1.036	.737	
high	17.65	8.56	3.049	.599	
scheduled (ideal)	2.84	1.70	.496	.328	
scheduled (imperfect)	4.47	5.16	.786	.499	

SECTION 8

REGIONAL EFFECTS OF AN IRRIGATION SCHEDULING SERVICE

Two basic questions regarding the economic viability were analyzed using the regional economic model. The first was to project the economic costs and changes in the amount and quality of return flows if all of the irrigation in the A and B District were required to be scheduled. The second was to determine the degree of voluntary adoption by farmers at varying scheduling and water costs.

POTENTIAL IMPACTS OF A SCHEDULING SERVICE

The basic economic and return flow information were estimated for each irrigation regime requiring that all fields be scheduled free of charge (Table 24). Crop yield coefficients for scheduling were based on the more conservative yield estimates developed in this study. The figures presented in Table 24 are three year averages (1973-75). Values by year are presented in Appendix Table A-1.

TABLE 24. ESTIMATED AVERAGE ANNUAL RETURNS TO LAND, MANAGEMENT
AND RISK FOR UNSCHEDULED AND SCHEDULED IRRIGATION
IN THE A AND B DISTRICT, 1973, 1974 AND 1975*

Average Annual Variable	Units	Unscheduled Irrigation	Scheduled Irrigation	
			Ideal	Imperfect
Returns to Land, Management & Risk	\$1,000	13.33	14.41	--
Irrigation Water:				
Use	AF (1,233 cm ³)	195.53	143.37	184.00
Cost	\$1,000	740.00	665.80	730.48
Irrigation Labor:				
Use	1,000 (Hours)	120.57	86.47	72.10
Cost	\$1,000	416.53	298.72	249.08

*Average irrigated acreage 65,133 (26,359 ha).

Changes in Financial Returns

The average annual returns to land, management and risk were increased by 1.08 million dollars, or \$16.58 per irrigated acre (.4 ha) by requiring a scheduling service that does not have implementation errors. Since the cost of most scheduling services do not exceed \$5.00 per acre (.4 ha) additional returns would appear to exceed the additional cost. However, these results do not account for the inherent element of risk either in yields or prices. Over the long-run, these may tend to even out and the results reported here may approximate the expected results but no attempt was made to quantify the statistical distribution of yields and prices. The use of conservative yield estimates in the LP model, however, may underestimate the expected benefits of an "ideal" scheduling service.

The increased annual returns to land, management and risk are attributable not only to increased yields, but also to substantial reductions in irrigation costs. To illustrate the relative importance of reduced costs and improved yields in evaluating the scheduling service, the results from the LP were compiled on a per acre (.4 ha) basis as follows.

<u>Component Change</u>	<u>Dollars Per Acre</u> (.4 ha)
Increased Value of Yields	13.63
Reduced Irrigation Labor Cost	1.81
Reduced Water Cost	<u>1.14</u>
Net Change in Annual Returns	16.58

The value of increased yields accounted for approximately 82 percent of the total increase in annual returns. This value is net of the increased harvest cost of \$1.44 per acre (.4 ha).

The average annual reduction in water and labor costs were \$2.95 per acre (.4 ha). The savings in these irrigation costs are almost as much as the cost of a scheduling service. Water costs were reduced only by 10.0 percent whereas total water use was reduced by 26.7 percent under the ideal scheduling regime. This disparity is due to the water pricing schedule of the A and B District which stipulates a fixed rate for the first three feet of water use. Since district water use was reduced from 197,000 acre-feet (an average of 3.05 acre feet per acre or $1.233 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) to 144,000 acre-feet (an average of 2.23 acre feet per acre or $2.75 \times 10^3 \text{ cm}^3/.4 \text{ ha}$) the reduction in water use would not reduce irrigation costs proportionately. A comparison of weighted average* water costs for unscheduled fields and average costs for scheduled fields indicates that the average crop water cost for the scheduled regime was equal to the minimum cost set by the irrigation district with the exception of alfalfa. Irrigation costs would have been reduced more if water cost were directly proportional to water use.

*Weighted by the water-use patterns of district farmers as shown earlier in Table 13.

The estimated impacts on irrigation costs of an imperfect scheduling regime are also included in Table 24 but no estimate was made on returns to land, risk and management. As explained in the description of the production submodel, yield predictions resulting from the imperfect scheduling case were not possible without a more sophisticated approach. Therefore the LP was run with the yield estimates that were used for the ideal scheduling service based on the assumption that the error would probably not affect yields substantially but would result in additional irrigation costs. If this assumption were true, the following cost and yield changes would result.

<u>Component Change</u>	<u>Dollars Per Acre</u> (.4 ha)
Increased Value of Yields	13.63
Reduced Irrigation Labor Cost	.15
Reduced Water Cost	<u>2.56</u>
Net Change in Annual Returns	16.34

The aggregate results from the LP indicated that farmers would irrigate as many times as they would without a scheduling system but they would apply substantially less water. These regional or aggregate results are heavily influenced by the changes that occur in irrigating alfalfa. This will be explained in the next section on return flows.

Changes in Return Flows

The estimated annual environmental consequences of the ideal scheduling service included substantial reductions in return flows particularly deep percolation (Table 25). The estimated sediment reduction was 37.5 percent which would also indicate reductions in fertilizers and pesticides in return flows. This would suggest that rates of application of these materials may be reduced under a scheduling regime.

Surface runoff and sediment load were estimated to decrease by 23 and 28 percent respectively under the imperfect scheduling regime but deep percolation and salt load were not affected to a great degree. The usual error in the imperfect regime is for farmers to irrigate less but apply more water per irrigation. When compared to the ideal regime, surface runoff and erosion reductions are about the same because of fewer irrigations but the larger application per set increases the deep percolation and salt load.

VOLUNTARY ADOPTION OF A SCHEDULING SERVICE

The foregoing analysis indicated that the district as a whole would profit from universal irrigation scheduling. However, it was also observed earlier (see Table 17) that in some situations a farmer might be better off not to use a scheduling service for some crops, but instead to adopt one of the three levels of unscheduled water use because it would be more profitable. As an example, the highest profit for alfalfa growers in 1973 was realized with high water use and no scheduling, rather than with scheduling. The most profitable strategy would depend upon the cost of water and scheduling

TABLE 25. ESTIMATED AVERAGE ANNUAL IRRIGATION RETURN FLOWS
IN THE A AND B DISTRICT, 1973, 1974, AND 1975

IN THE A AND B DISTRICT, 1973, 1974, AND 1975				
Average Annual Variable	Units	Unscheduled Irrigation	Scheduled Irrigation	
			Ideal	Imperfect
Surface Runoff:				
Amount	1,000 AF (1,233,000 cm ³)	42.26	29.28	32.50
Sediment Load	1,000 Tons (907 Metric Tons)	36.37	27.73	26.10
Deep Percolation:				
Amount	1,000 AF (1,233,000 cm ³)	48.73	11.27	44.00
Salt Load	1,000 Tons (907 Metric Tons)	42.70	28.53	43.20

and the value of the scheduling yield differential. Therefore the analysis was repeated allowing the LP to select the optimum irrigation regime for each crop given a set of water and scheduling costs.

The voluntary adoption of a scheduling service would also depend on the relationship between the per hectare cost of providing the service and the total acreage being scheduled by the firm. The cost characteristics of the scheduling industry were not invested in this study but if sufficient economies of size existed, requiring farmers to participate would lower the per hectare cost. A policy of compensating farmers to participate would also be more socially desirable if per unit costs decreased as the size of operation increased.

Variable Scheduling Costs

The cost of scheduling was parametrically varied in the LP model from zero to \$5.00 to estimate average annual changes in the number of acres (.4 ha) scheduled and the amount of return flows.*

Demand for a Scheduling Service--

The cost of scheduling affected the number of acres (ha) scheduled differently in each year (Figure 26). However, the composite results from the three year analysis indicates that an increase in the price of scheduling from zero to \$5.00 would reduce the number of scheduled acres (ha) from approximately 45,000 acres (18,212 ha) to 20,000 acres (8,094 ha). This relationship would be important to a private company in the scheduling business. The general relationship of price to scheduled acres can be captured by estimating the elasticity of demand as follows:

*All results of the parametric analysis are presented in Appendix A.



FIGURE 26. Estimated scheduled acreage and scheduling cost, A&B District, 1973, 1974 & 1975.

$$\Sigma_D = \frac{\% \text{ Change in Scheduled Acres}}{\% \text{ Change in Cost}} \quad (48)$$

This measures the sensitivity of scheduled acres (ha) to cost for specific ranges of the demand functions.

The demand function was estimated from the corner solution values illustrated in Figure 26. The elasticities were estimated from the demand function for various scheduling costs. These values are as follows:

<u>Scheduling Cost</u> <u>(\$/Acre or .4 ha)</u>	<u>Elasticity of Demand</u>
\$1.00	-.059
2.00	-.125
3.00	-.286
4.00	-.502
5.00	-.800

At \$3.00 or less, the effect of price on the amount of scheduled acres is negligible but as the cost approaches \$5.00, the percent change in scheduled acres is almost as great as the percent change in cost. Therefore, if the scheduling service were supplied in the A and B District at current market cost, about 38 percent of the total irrigated acres would be scheduled.

The effect of varying scheduling costs would not effect regional returns to a great extent (Table A-1.). The average annual returns for 1973, 74 and 75 without a scheduling service was \$13.3 million or \$203.36 per acre (.4 ha). The average annual returns were increased relative to the unscheduled regime by a zero cost scheduling service to \$14.52 million or \$222.92. An increase in the cost to \$5.00 would decrease average annual returns to \$221.44 per acre (.4 ha).

Irrigation Water Use--

Applied irrigation water that does not infiltrate the soil or remain in the root zone will pick up salts and sediment and carry them to ground water aquifers or surface streams. Reducing return flows depends on applying the right amount of water at the right time. Surface runoff will result if water in excess of the soils absorbtion ability is applied. This requires careful monitoring of the amount applied during any one irrigation. On the other hand, deep percolation will result if water is absorbed in excess of the soils water holding capacity. A certain amount of deep percolation is required during the season to leach salts from the root zone. This can usually be achieved applying water in excess of the water holding capacity. Controlling deep percolation depends on irrigating when the root zone is sufficiently dry to hold the amount of water infiltrated. Usually the total amount of water applied in a season in a given district is indicative of the amount of return flows.

As reported earlier, the estimated annual water use in the A and B District without a scheduling service was about 195,500 acre feet ($241,051 \times 10^3 \text{ cm}^3$) and about 120,000 acre feet ($147,960 \times 10^3 \text{ cm}^3$) if a scheduling system was imposed. This represents about 3.00 and 1.84 acre feet (3.67×10^3 and $2.27 \times 10^3 \text{ cm}^3$) per crop acre (.4 ha) per year. The 1.84 acre feet ($2.27 \times 10^3 \text{ cm}^3$) per year application is sufficient for crop ET supplemented by normal rainfall but not sufficient for leaching salts beyond the root zone. In the case of a voluntary scheduling service charging \$5.00 per acre (.4 ha), the estimated average annual water use was about 178,200 acre feet ($219,721 \times 10^3 \text{ cm}^3$). This amount was reduced to about 146,300 acre feet ($180,388 \times 10^3 \text{ cm}^3$) if the service was offered at no charge (Figure 27).

Scheduling Cost and Return Flows--

Irrigation return flows, however, are significantly effected by changes in scheduling costs. At zero cost, average annual deep percolation was estimated at 25,000 acre feet and increased to 37,600 acre feet ($30,825 \times 10^3$ and $46,361 \times 10^3 \text{ cm}^3$) as a result of a \$5.00 scheduling cost (Figure 28). The sensitivity of deep percolation to scheduling costs was estimated by calculating the percent change in deep percolation resulting from a percent change in scheduling cost.

<u>Scheduling Cost</u> <u>\$ Per Acre (.4 ha)</u>	<u>% Change in Deep Percolation</u> <u>% Change in Scheduling Cost</u>
1	.048
2	.087
3	.166
4	.231
5	.285

These results indicate that deep percolation is not as sensitive to scheduling costs as the amount of irrigation scheduling was. However, the level of cost is important if the amount of deep percolation is an environmental concern or the resulting water table presents drainage problems for other farmers.

The amount of salts in the deep percolation is effected even less by scheduling costs than was the amount of deep percolation. This occurs because the bulk of the salts are leached from the root zone by the first amount of water to pass through the root zone and subsequent leaching will pick up proportionally fewer salts. The estimated average salt load at zero scheduling cost is about 36,000 tons (32.659 metric tons) annually and increases to about 43,000 tons (39,010 metric tons) at a cost of \$5.00 (Figure 29). This is a 18 percent increase in salt load as compared to a 50 percent increase in deep percolation from the same cost change.

The average increase in the amount of runoff and sediment load from varying scheduling costs was similar to the change that occurred in salt load (Figure 30). Runoff ranged from about 34,400 to 39,700 acre feet ($42,415 \times 10^3$ to $48,950 \times 10^3 \text{ cm}^3$) (15.4 percent) and sediment increased from 29,200 to 34,000 tons (26,490 to 30,845 metric tons) (16.4 percent) as scheduling costs were increased from zero to \$5.00.



IRRIGATION WATER USE (1,000 ACRE-FEET (1233 x 10³ cm³))

FIGURE 27. Estimated water use and scheduling cost, A&B District, 1973, 1974 & 1975.

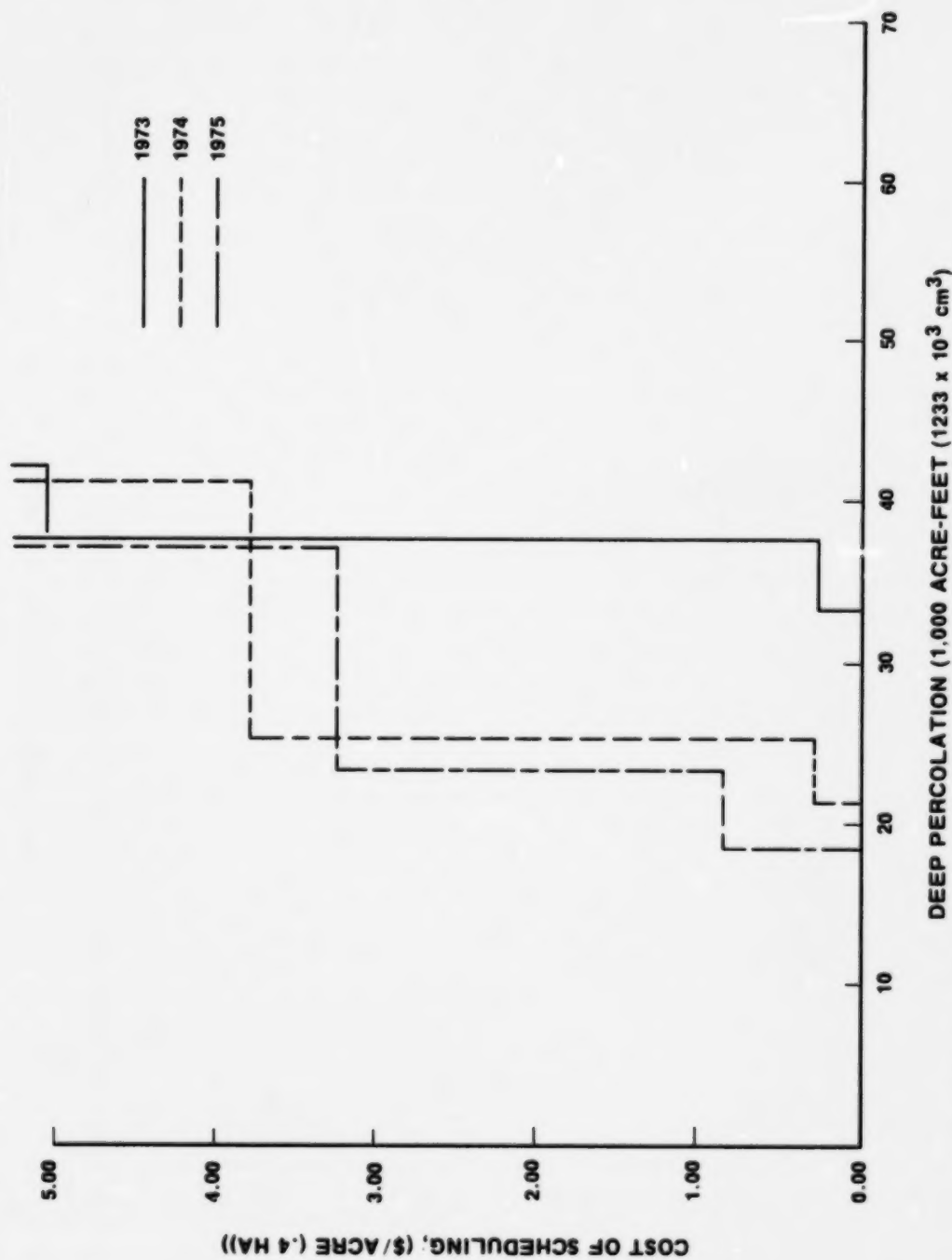


FIGURE 28. Estimated deep percolation as a function of scheduling cost, A&B District, 1973, 1974 & 1975.

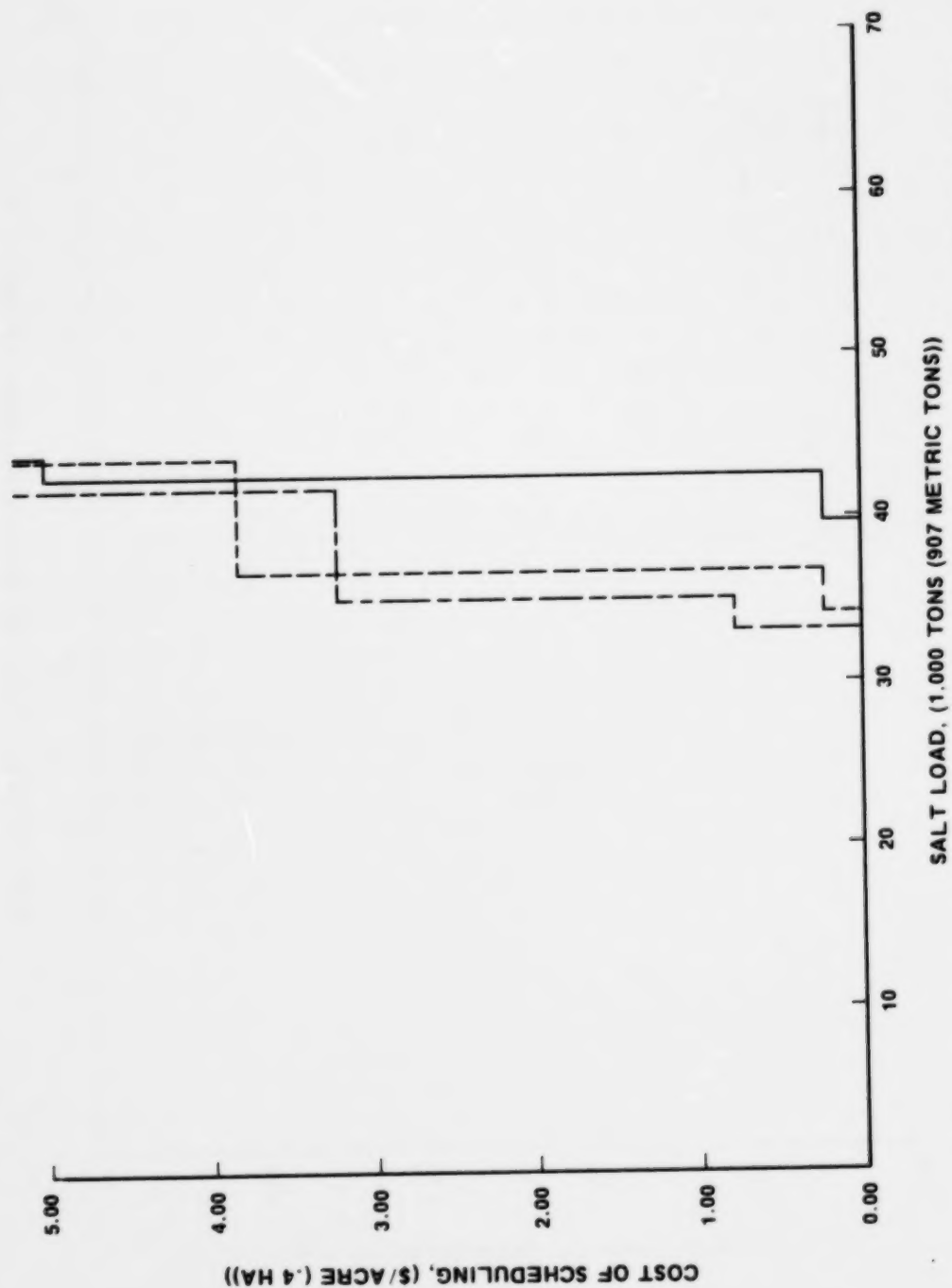
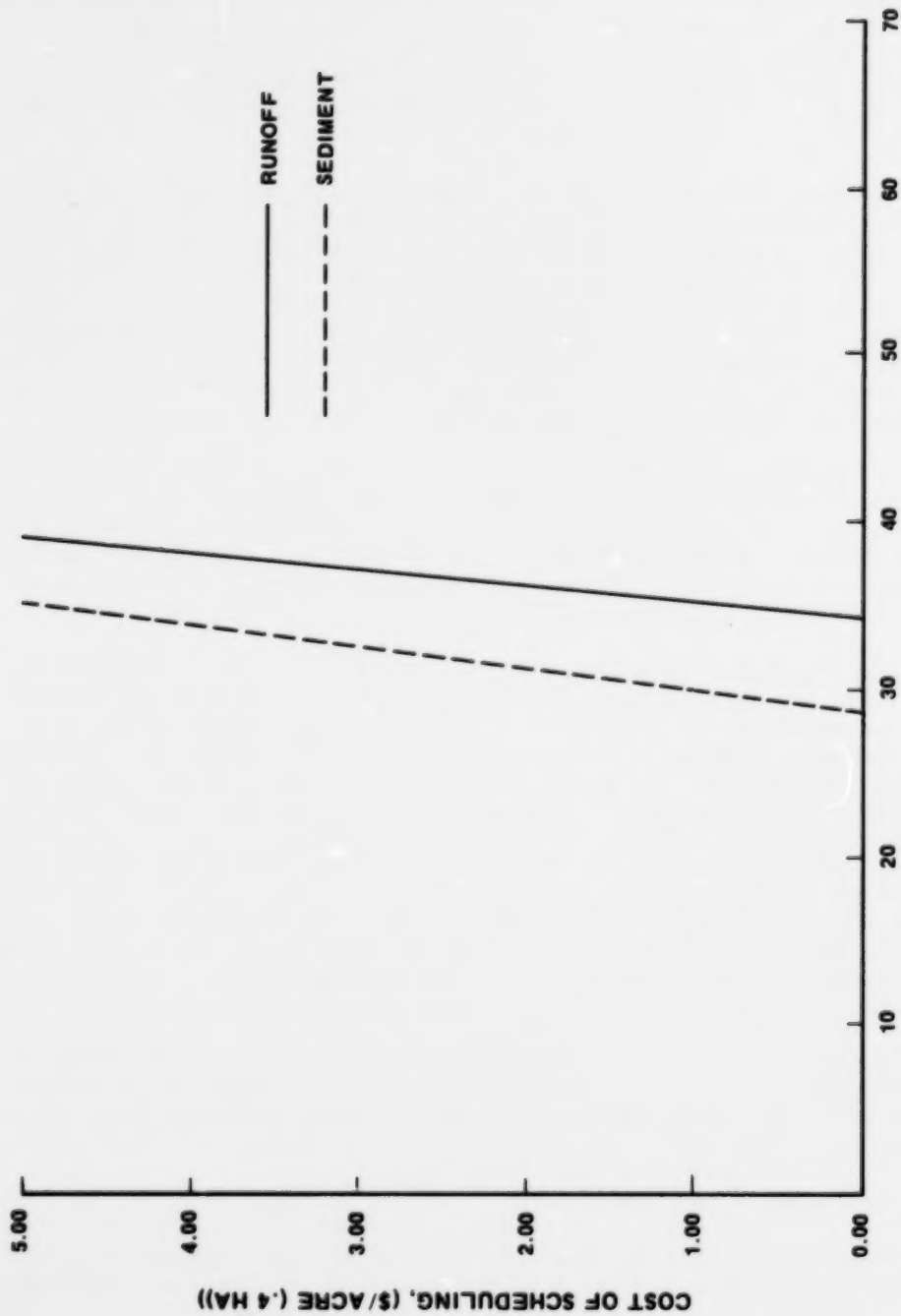


FIGURE 29. Estimated salt load as a function of scheduling cost, A&B District, 1973, 1974 & 1975.



RUNOFF AND SEDIMENT LOAD, (1,000 ACRE-FEET OR TONS ($1233 \times 10^3 \text{ cm}^3$ or 907 METRIC TONS))

FIGURE 30. Estimated average annual surface runoff and sediment load, A&B District, 1973, 1974 & 1975.

REDUCING RETURN FLOWS BY SCHEDULING

Irrigation scheduling could be an effective tool in managing return flows because the program objective is to keep the soil moisture higher than the permanent wilting point and below field capacity with a minimum number of irrigations. This results in a minimum of return flows without reducing acreage or yields. The main problem of course is the ability of each farmer to implement each scheduling order with sufficient precision. As described earlier, errors in timing and application amounts can negate most of the crop yield or return flow benefits.

To summarize the effects of the scheduling program, water use and return flows resulting from the various scheduling policies in the A and B District were compared with the results with no scheduling service (Table 26). The results from the regional economic model indicate that scheduling and the degree to which it is implemented has a dramatic effect on reducing return flows. Water use was estimated at 195,530 acre feet ($241,088 \times 10^3 \text{ cm}^3$) without scheduling and 143,370 acre feet ($176,775 \times 10^3 \text{ cm}^3$) with required scheduling. Water use varied between these amounts for voluntary scheduling with costs ranging from zero to \$5.00.

The scheduling cost proved to be a significant factor in determining the aggregate amount of irrigation that will be scheduled. This is probably true in the A and B District case for one principal reason. First, the irrigation practices normally applied in the District are reasonably efficient and increasing the charge for the scheduling service will make it less profitable than normal irrigation practices.

The estimated 26.7 percent reduction in water use as a result of a required scheduling service reduced the estimated deep percolation by 76.9 percent, salt load by 33.7 percent, surface runoff by 30.7 and sediment load by 37.5 percent. Similarly, a voluntary scheduling service had proportional effects on return flows. Although the estimated return flows seem to vary substantially from scheduling, this analysis could underestimate the true yield and return flow benefits in the irrigated west. Many irrigation districts hold water rights in excess of ET and percolation requirements and do not charge farmers on the basis of water use. This promotes inefficient water use and opportunities for large amounts of return flows to be generated. An imposed scheduling service in these areas would have a substantial effect on return flows and bypass the more complex legal and institutional questions involved with price and water allocations.

The cost of reducing salt and sediment loads were not calculated as the cost of scheduling was not estimated. However, for costs from \$0.00 to \$5.00 per acre returns to land, management and risk increased from the no scheduling case.

VARIABLE WATER COSTS AND SCHEDULING

The theoretical economic model formulated earlier suggests that variable water costs should have an effect on the amount of irrigation scheduling and

TABLE 26. ESTIMATED AVERAGE ANNUAL IRRIGATION WATER USE AND RETURN FLOWS
ALTERNATIVE SCHEDULING POLICIES, A AND B DISTRICT

Scheduling Policy	Cost (\$/Acre) (\$4/ha)	Water Use (1,000 AF) (1,233 x 10 ³ cm ³)	Deep Percolation (1,000 AF) (1,233 x 10 ³ cm ³)	Salt		Surface		Sediment	
				Load (1,000 Tons) (907 Metric Tons)	Load (1,000 Tons) (907 Metric Tons)	Runoff (1,000 AF) (1,233 x 10 ³ cm ³)	Runoff (1,000 AF) (1,233 x 10 ³ cm ³)	Load (1,000 Tons) (907 Metric Tons)	Load (1,000 Tons) (907 Metric Tons)
Required	0.00	143.37	11.27	28.53	29.28			22.73	22.73
Voluntary	0.00	146.30	25.08	36.20	34.42			29.23	29.23
"	1.00	152.67	28.83	27.53	35.48			30.19	30.19
"	2.00	159.04	30.09	38.86	36.53			31.15	31.15
"	3.00	165.41	32.59	40.19	37.59			32.11	32.11
"	4.00	171.78	35.09	41.52	38.65			33.07	33.07
"	5.00	178.15	37.60	42.84	39.71			34.03	34.03
Unscheduled		195.53	48.73	42.70	42.26			36.37	36.37

the generation of return flows. If farmers are profit maximizers and are aware of irrigation alternatives and relationships, increasing water costs will result in less water being applied as more water saving practices and technologies are utilized. The results from the regional economic model did confirm this relationship. The cost of water was varied from \$3.00, which approximates the current cost, to \$20.00 per acre foot ($1.233 \times 10^3 \text{ cm}^3$) to determine water use, level of scheduling adoption and return flows (Table 27). Estimated annual water use decreased from 195,000 acre feet ($240,435 \times 10^3 \text{ cm}^3$) under the present schedule to 134,670 acre feet ($166,048 \times 10^3 \text{ cm}^3$) (31 percent) at a \$20.00 cost. The decreased water use was primarily the result of the scheduling alternatives available for each crop. At \$20.00, most of the District acreage is scheduled.

Return flows were reduced accordingly. Deep percolation was estimated at 11,440 acres (4,630 ha) if the water cost was \$20.00 per acre foot ($1.233 \times 10^3 \text{ cm}^3$). This represents a 76.5 percent reduction and compares to the results obtained for the required scheduling policy. Surface runoff was also reduced by amounts similar to those achieved under a mandatory scheduling policy.

In summary, changing water costs could effect the amount of irrigation scheduling in a district. Sufficient water savings are realized by scheduling to justify the service on purely economic criteria if water costs are sufficiently high. However, water prices in the west are traditionally much lower than the \$20.00 per acre foot ($1.233 \times 10^3 \text{ cm}^3$) hypothesized in this analysis. Water prices are usually established by water agencies to allocate diversion and distribution costs to individual water customers without considering the value of water in alternative uses or the social costs of return flows. The present price structure, based primarily on diversion costs, will generally result in more diversions, greater agricultural production, increased net farm incomes and larger return flows in a specific area than would occur under higher water prices. Markets for the transfer of water rights and use would establish an opportunity cost of water. However, markets for water do not generally exist.

The objectives of Section 208 of Public Law 92-500 are to decrease the externalities of nonpoint sources of pollution by requiring the specification of methods to control runoff from agricultural and silvicultural lands. These controls will be a set of "best management practices" (BMP) applied to achieve the water quality goals of PL 92-500. The BMP being considered by the agencies conducting Section 208 analysis are specific soil and water-use management techniques and physical treatment structures. Charging water prices to achieve different use patterns and/or environmental results have not been considered. The agency concern with identifying the physical pollution effects of changing irrigation practices and ignoring the possibilities of economic incentives is understandable. Many of the agencies do not favor pricing policies as pollution control alternatives because they are politically undesirable and the income and equity effects are unknown. However, adjusting irrigation water costs to account for the social costs imposed by return flow disposal has been suggested before (Horner and English, 1976). Results from this study indicate that sufficient correlation exists between return flows and water use to price irrigation water to achieve desired environmental results.

TABLE 27. ESTIMATED AVERAGE ANNUAL IRRIGATION WATER USE, SCHEDULING ACTIVITY, RETURN FLOWS, SEDIMENT LOSS AND SALT LOAD FOR ALTERNATIVE WATER COSTS, A AND B DISTRICT*

Water Cost (\$/AF) ($\$/1.233 \times 10^3 \text{ cm}^3$)	Acres Scheduled** (1,000 Acres) (404.7 ha)	Water Use (1,000 AF) ($1,233 \times 10^3 \text{ cm}^3$)	Deep Percolation (1,000 AF) ($1,233 \times 10^3 \text{ cm}^3$)	Surface Runoff	Sediment Loss (1,000 Tons) (907.2 Metric Tons)	Salt Load
Present Schedule	Not Scheduled					
3.00	54.45	195.30	48.73	42.27	36.37	42.70
5.00	55.37	162.30	19.47	32.56	25.36	20.97
10.00	57.66	150.92	18.53	31.61	25.03	29.90
15.00	59.96	142.80	16.17	29.21	24.21	27.22
20.00	62.23	134.67	13.81	26.82	23.39	24.54
			11.44	24.42	22.56	21.85

*Scheduling is provided at zero cost.

**Alfalfa acreage would be irrigated under the scheduling regime at low water cost but revert to a low water application rate at higher cost (Table Appendix A-2). This is not reflected in these average data. These relationships were estimated by regression analysis using values of the corner solutions and cannot be compared to values reported in Table 25.

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APPENDIX A

TABLE A-1. CROP ACREAGE, RETURNS, WATER USE AND IRRIGATION RETURN FLOWS RESULTING FROM SCHEDULED IRRIGATION AT VARYING SCHEDULING COSTS

Year	Policy	Total Crop Acres (1,000 Acres)	No. of Schedules (404.7 ha)	Returns To Land Mgmt. & Risk (\$ Millions)	Percent Change From			Percent Change From			Percent Change From			Labor Use (1,000 Hours)
					Sched- uling	No Sched- uling	Surface Runoff (1,000 Acre Feet) (1,233 x 10 ³ cm ³)	Deep Perco- lation	Sched- uling	Loss	Sediment	No Sched- uling	Total Dis- solved Solids (1,000 Tons) (907.2 Metric Tons)	
1973	No Scheduling	64.5	0.0	12.14			42.8	47.8					42.7	120.7
	Scheduling Cost: \$0.00/A	64.5	40.4	13.24	2.6	172.7	-12.9	36.58	-14.0	33.33	-34.0	27.2	-17.8	104.8
	Scheduling Cost: \$0.25/A	64.5	22.3	13.23	2.6	185.7	-6.4	40.33	-5.2	38.53	-19.4	32.8	-1.2	112.2
	Scheduling Cost: \$5.00/A	64.5	10.4	13.13	1.8	192.5	-2.9	40.90	-3.8	43.02	-10.0	32.0	-3.5	118.5
	Scheduling Cost: \$0.00/A	64.5	64.5	14.69	13.9	122.3	-38.4	29.98	-29.5	11.53	-75.9	22.2	-33.0	87.2
	Scheduling Cost: \$4.00/A	64.5	63.5	14.45	12.0	123.4	-37.8	30.23	-28.9	12.41	-74.0	22.5	-32.0	88.0
	Scheduling Cost: \$4.75/A	64.5	44.5	14.40	11.6	169.0	-14.8	35.53	-16.5	30.54	-36.1	25.6	-22.9	102.4
1974	Scheduling Required	64.5	64.5	13.18	2.2	122.3	-38.4	29.98	-29.5	11.53	-75.9	22.2	-33.0	87.2
	No Scheduling	65.3	0.0	16.61									41.9	118.3
	Scheduling Cost: \$0.00/A	65.3	50.0	17.96	2.7	133.6	-32.3	33.16	-22.9	21.25	-57.9	28.3	-20.9	92.6
	Scheduling Cost: \$0.25/A	65.3	37.3	17.95	2.6	142.5	-27.7	35.79	-16.8	25.01	-50.4	32.2	-10.1	97.8

Continued--

TABLE A-1.--CONTINUED

TABLE A-1.1.--CONTINUED																				
Year	Policy	Total Crop Acres (1,000 Acres) (404.7 ha)	No. of Sched- uled Acres	Returns To Land Mgmt. & Risk (\$) (Millions)	Percent Change		Irri- gation Water Used (\$)	Percent Change		Surface Runoff (1,000 Acre Feet) (1,233 x 10 ³ cm ³)	Percent Change		Deep Perco- lation (1,000 Acre Feet) (1,233 x 10 ³ cm ³)	Percent Change		Sedi- ment Loss (1,000 Tons) (907.2 Metric Tons)	Percent Change		Total Dis- solved Solids (1,000- Hours)	Labor Use (1,000- Hours)
					From	No		From	No		From	No		From	No					
					Sched- uling	Sched- uling		Sched- uling	Sched- uling		Sched- uling	Sched- uling								
1974 Scheduling Cost:																				
	\$3.75/A	65.3	19.0	17.82	1.9	186.3		-5.4	40.90		-4.9	42.48		-15.8	35.2		-1.9	44.9		112.7
Scheduling Cost:																				
	\$0.00/A	65.3	65.3	19.86	13.2	119.2		-39.5	29.30		-31.9	10.98		-78.2	22.4		-37.6	28.2		83.5
Scheduling Cost:																				
	\$5.00/A	65.3	65.3	19.54	11.7	119.2		-39.5	29.30		-31.9	10.98		-78.2	22.4		-37.6	28.2		83.5
Scheduling Required																				
		65.3	65.3	17.74	1.4	119.2		-39.5	29.30		-31.9	10.98		-78.2	22.4		-37.6	28.2		83.5
1975 No Scheduling																				
		65.6	0.0	11.23		191.3			41.3			48.0			37.6			43.5		122.7
Scheduling Cost																				
	\$0.00/A	65.6	54.3	12.35	3.2	129.0		-32.5	31.39		-23.9	18.84		-60.8	27.9		-21.2	33.1		95.5
Scheduling Cost:																				
	\$0.75/A	65.6	39.4	12.31	2.8	139.8		-26.9	34.48		-16.4	23.28		-51.5	32.5		-8.3	35.9		101.6
Scheduling Cost:																				
	\$3.25/A	65.6	23.4	12.22	2.1	178.3		-6.8	18.98		-5.5	38.60		-19.7	35.0		-1.1	42.8		113.8
Scheduling Cost:																				
	\$0.00/A	65.6	65.6	13.85	15.7	118.6		-38.0	28.57		-30.8	11.30		-76.5	23.6		-33.5	28.4		88.7
Scheduling Cost:																				
	\$5.00/A	65.6	65.6	13.52	12.9	118.6		-38.0	28.57		-30.8	11.30		-76.5	23.6		-33.5	28.4		88.7
Scheduling Required																				
		65.6	65.6	12.30	2.3	118.6		-38.0	28.57		-30.8	11.30		-76.5	23.6		-33.5	28.4		88.7

TABLE A-2. CROP ACREAGE, RETURNS, WATER USE AND IRRIGATION RETURN FLOWS RESULTING FROM SCHEDULED IRRIGATION AT VARYING WATER COSTS

Year	Policy	Total Crop Acres (1,000 Acres)	No. of Schedules	Returns To Land Mgmt. & Risk (\$)	Percent Change From No Scheduling	Irrigation Water Used (1,000 Acre Feet)	Percent Change From No Scheduling	Surface Runoff (1,000 Acre Feet)	Deep Percolation (1,000 Acre Feet)	Percent Change From No Scheduling	Sediment Loss (1,000 Tons)	Percent Change From No Scheduling	Total Dissolved Solids (1,000 Tons)	Percent Change From No Scheduling	Labor Use (1,000 Hours)
1973	No Scheduling	64.5	0.0	12.14		198.3		42.5	47.8		35.3		42.7		120.7
	Water Cost: \$3.00/AF	64.5	40.4	13.42	4.0	207.2	-12.9	40.3	33.2	-30.6	27.2	-7.8	39.3	-17.8	106.8
	Water Cost: \$4.00/AF	64.5	59.4	13.26	2.8	152.5	-35.9	31.3	15.0	-68.5	24.2	-27.0	31.1	-34.9	90.4
	Water Cost: \$10.00/AF	64.5	63.5	12.34	-4.3	148.2	-37.8	30.2	12.4	-74.0	22.5	-32.0	29.5	-38.4	88.0
	Water Cost: \$11.00/AF	64.5	45.5*	12.22	-5.3	124.7	-47.6	20.8	8.0	-83.2	21.3	-35.9	19.1	-60.1	124.7
	Water Cost: \$3.00/AF	64.5	64.5	14.89	15.4	146.7	-38.4	30.0	11.5	-75.9	22.2	-33.0	28.9	-39.4	87.3
	Water Cost: \$15.00/AF	64.5	45.5	31.15	1.9	124.7	-47.6	20.8	8.0	-83.2	21.3	-35.9	19.1	-60.1	94.6
	No Scheduling	65.3	0.0	16.61		197.0		43.0	50.4		36.2		41.9		118.3
1974	Water Cost: \$3.00/AF	65.3	50.0	18.16	3.8	160.1	-32.3	33.2	21.3	-57.9	28.4	-20.9	34.6	-29.7	160.1
	Water Cost: \$9.00/AF	65.3	44.8	18.0	42.9	125.0	-47.1	21.0	9.6	-81.0	22.1	-38.3	19.7	-59.9	92.3

Continued--

*18,985 acres of alfalfa went from scheduled to low H₂O app. and 1,006 acres of peas from medium H₂O app. to scheduled.

TABLE A-2.--CONTINUED

Year	Policy	Total Crop Acres (1,000 Acres)	No. of Sched- uled Acres (404.7 ha)	Returns To Land Mgmt. & Risk (\$)	Percent Change From No Sched- uling (Millions)	Irri- gation Water Used (1,000 Acre Feet)	Surface Runoff (1,000 Acre Feet)	Percent Change From No Sched- uling (1,233 x 10 ³ cm ³)	Deep Perco- lation (1,000 Acre Feet)	Percent Change From No Sched- uling (907.2 Metric Tons)	Sedi- ment Loss (1,000 Tons)	Total Dis- solved Solids (1,000 Tons)	Percent Change From No Sched- uling (1,000 Tons)	Labor Use (1,000 Hours)
1974	Water Cost: \$32.00/AF	65.3	47.0	17.9	+2.3	121.8	20.5	-48.5	-52.4	7.6	21.5	18.7	-40.1	90.6
	Water Cost: \$3.00/AF	65.3	65.3	20.13	15.0	143.0	29.3	-39.5	-31.9	11.0	22.4	28.3	-37.6	83.5
	Water Cost: \$12.00/AF	65.3	47.0	18.85	7.8	121.8	20.5	-48.5	-52.4	7.6	21.4	18.7	-40.1	121.8
1975	No Scheduling	65.6	0.0	11.23		191.3	41.3			48.0	37.6	43.5		122.7
	Water Cost: \$3.00/AF	65.6	54.3	12.57	5.0	154.8	31.4	-32.5	-23.9	18.8	27.9	33.1	-21.2	95.5
	Water Cost: \$5.00/AF	65.6	63.9	12.27	2.5	144.7	29.0	-36.9	-29.8	12.8	24.0	29.2	-32.1	90.0
	Water Cost: \$11.00/AF	65.6	47.9	11.42	-4.6	126.1	21.2	-45.0	-48.5	9.8	23.2	20.8	-34.4	96.3
	Water Cost: \$27.00/AF	65.6	49.5	9.41	-21.3	123.7	20.8	-46.1	-49.5	8.3	22.7	20.0	-35.8	95.0
	Water Cost: \$3.00/AF	65.6	65.6	14.13	18.0	142.3	28.6	-38.0	-30.8	11.3	23.6	28.4	-31.4	142.3
	Water Cost: \$15.00/AF	65.6	49.5	12.45	4.0	123.7	20.8	-46.1	-49.5	8.3	22.7	20.0	-35.8	123.7